SURVEY OF UNITED STATES SONIC BOOM OVERFLIGHT EXPERIMENTATION

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SURVEY OF UNITED STATES SONIC BOOM OVERFLIGHT EXPERIMENTATION

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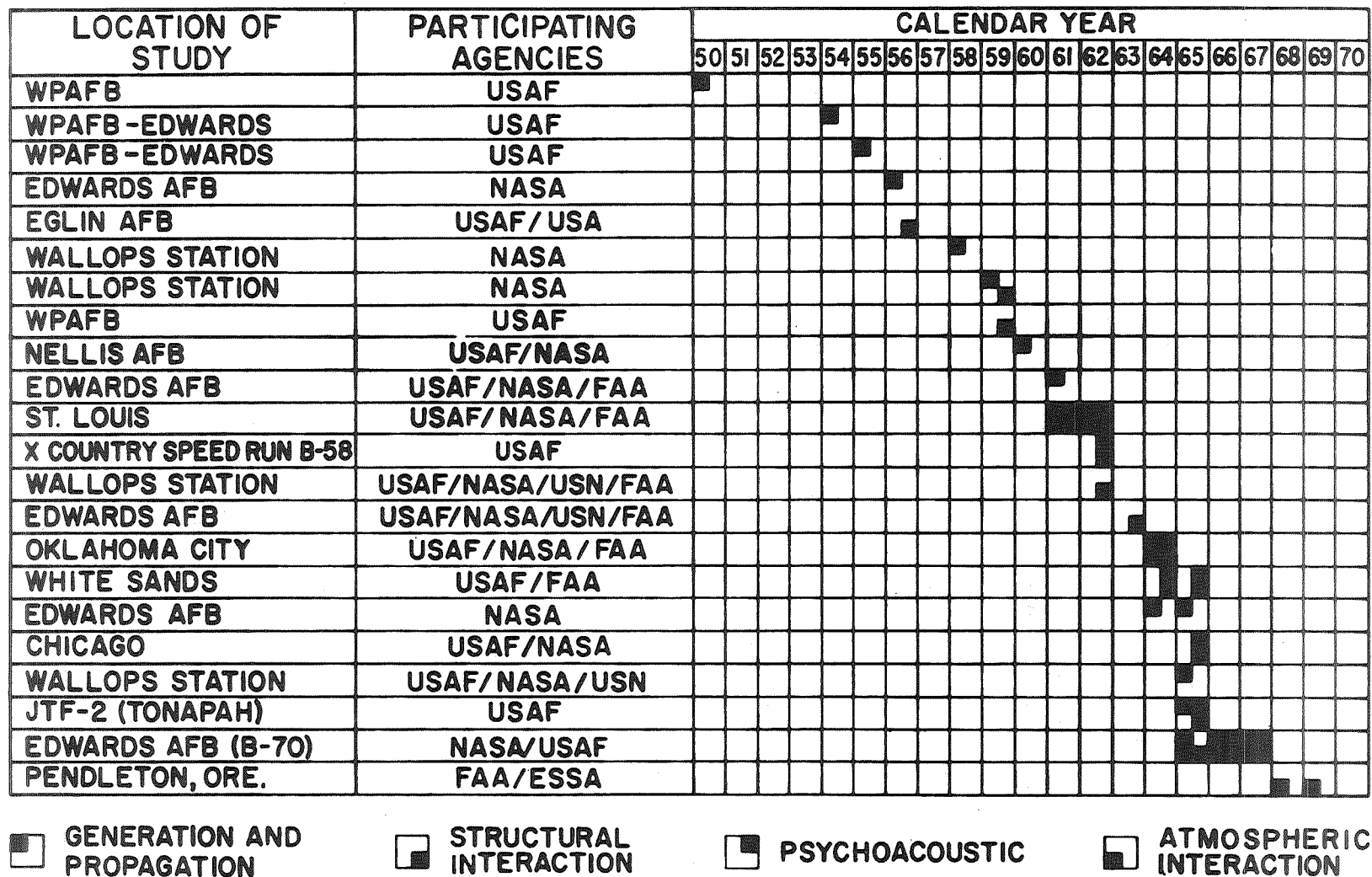Hampton, Va.

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I. INTRODUCTION

For 22 years man has had the capability of maintaining steady state flight at speeds faster than the speed of sound. For almost as many years, continuing programs of supersonic overflight experimentation have been conducted to improve our knowledge and understanding of the sonic boom, a phenomena which is inescapably associated with super- sonic flight. Several survey papers exist, for example, References 1 through 3, which have reviewed the chronology and the significant find- ings from overflight experimentation. The present paper will utilize much of the material previously presented in those references; however, it is the authors' intent to add new and recent material which will, in effect, update the previous papers. In addition, some recent de- velopments in the claims and legal activity associated with this ex- perimentation permit us to obtain an up-to-date view of the legal and social costs associated with the test programs. Other recent develop- ments in the field of sonic boom overpressure measuring instrumenta- tion and in the theoretical methods of signature prediction are included. These developments are expected to facilitate future sonic boom over- flight studies and will enhance our ability to theoretically interpret the resulting experimental findings.

II. CHRONOLOGICAL REVIEW

A graphical summary of the United States sonic overflight research is presented in Figure 1. This figure is an adaptation of a similar figure used by Nixon in Reference 3. The figure has been arranged to indicate the areas of emphasis during the specific overflight programs. The shading indicates programs directed at understanding the flow phe- nomena related to the process of sonic boom generation and propagation, programs directed towards investigations of structural interactions with sonic boom, programs directed towards psychoacoustic investiga- tions, and finally, programs designed to improve our understanding of the interaction of the sonic boom with the earth's atmosphere. From the figure, it is observed that the initial programs were related pri- marily to military investigations and dealt to a large extent with the problem of sonic boom generation and propagation. The reason for this was that the initial sonic booms were generally accidental, generated by military aircraft, and accordingly, it was desirable to determine the conditions associated with the generation of sonic booms. As a result, the military agencies found that it was possible to avoid sonic boom accidents by the conduct of training missions over sparsely pop- ulated areas and by having the aircraft fly at sufficiently high alti- tudes thereby minimizing the effects of sonic booms on the ground ob- server. The next period in the overflight research during the latter 1950's represented the initiation of active participation by the National Aeronautics and Space Administration in investigations of a phenomenon associated with sonic booms. This research was more gen- eral in nature and primarily directed at evaluating the influence of

LOCATION OF STUDY	PARTICIPATING AGENCIES	CALENDAR YEAR
		50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70
WPAFB	USAF	50
WPAFB–EDWARDS	USAF	54
WPAFB–EDWARDS	USAF	55
EDWARDS AFB	NASA	56
EGLIN AFB	USAF/USA	57
WALLOPS STATION	NASA	59
WALLOPS STATION	NASA	60
WPAFB	USAF	60
NELLIS AFB	USAF/NASA	61
EDWARDS AFB	USAF/NASA/FAA	62
ST. LOUIS	USAF/NASA/FAA	62
X COUNTRY SPEED RUN B-58	USAF	62
WALLOPS STATION	USAF/NASA/USN/FAA	63
EDWARDS AFB	USAF/NASA/USN/FAA	64
OKLAHOMA CITY	USAF/NASA/FAA	64
WHITE SANDS	USAF/FAA	65
EDWARDS AFB	NASA	65
CHICAGO	USAF/NASA	65
WALLOPS STATION	USAF/NASA/USN	65
JTF-2 (TONAPAH)	USAF	65–67
EDWARDS AFB (B-70)	NASA/USAF	66–68
PENDLETON, ORE.	FAA/ESSA	68–69

Legend:
- ▣ GENERATION AND PROPAGATION
- ◱ STRUCTURAL INTERACTION
- ◩ PSYCHOACOUSTIC
- ◪ ATMOSPHERIC INTERACTION

CHRONOLOGY OF U.S. SONIC-BOOM RESEARCH

Figure 1

aircraft operational parameters such as gross weight, Mach number, and altitude on the sonic boom overpressure magnitude.

In 1960, the projects "Little Boom" and "Big Boom" were conducted at the Nellis Air Force Base. These studies were directed towards the evaluation of the feasibility of using the sonic boom as a weapon and as such provided an excellent opportunity to study potential structural damage and physiological reactions in the presence of extreme sonic boom overpressures. The greatest overpressure reached in this series of tests was approximately 120 lbs. per square foot which was the largest overpressure recorded to that date. After these tests, the overflight programs were influenced by considerations of the development of a commercial supersonic transport. In particular, it is noted that the flight experiments over St. Louis, Oklahoma City, and finally at the Edwards Air Force Base were conducted to evaluate the psychoacoustic reaction of community groups to repeated supersonic overflights. More recent flights, including the series which terminated in 1967, were conducted at Edwards AFB. These tests were highlighted by the inclusion of the XB-70 aircraft, which is the largest American supersonic aircraft flying today. The current experimentation in the Pendleton, Oregon, area is utilizing target of opportunity flights of military aircraft to evaluate the atmospheric effects on sonic booms.

III. SONIC BOOM GENERATION AND PROPAGATION

Sonic booms experienced by a ground observer are the manifestation of the aerodynamic flow field about a body traveling at supersonic speeds. In an idealized uniform atmosphere, the sonic boom felt at the ground would be a result of the geometric spreading of the acoustic energy of the supersonic flow field. In the real atmosphere, the sonic boom signature is changed by atmospheric temperature gradients, influenced by the wind profile, and altered by propagation through turbulent air masses. The overflight studies directed at understanding the physics of sonic boom generation and propagation have contributed considerable insight into the mechanisms involved. Many of the overflight studies have resulted in quantitative evaluations of the mechanisms, however, some of the mechanisms are understood only in a qualitative manner.

a. Signature Characteristics. Typical signatures measured during overflight programs are shown in Figure 2. It is noted that regardless of the aircraft size, the signatures in general can be categorized as "peaked," "normal," or "rounded." It is interesting to observe that for these signatures, the deviations from a smooth N wave related to the bow shock and the tail wave are similar. This fact was pointed out by Kane and Palmer in Reference 4 and was postulated as a basis for contributing the entire distortion of the signature to propagation through atmospheric inhomogeneities. The signatures shown in the figure for the F-104, B-58, and the
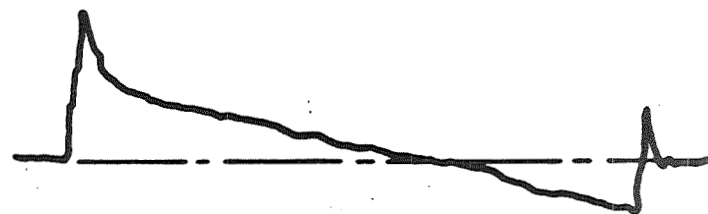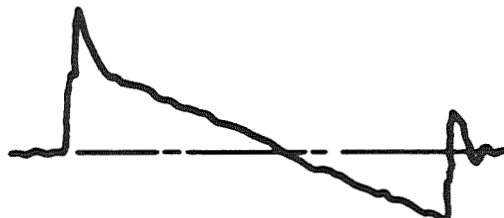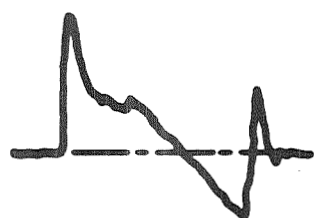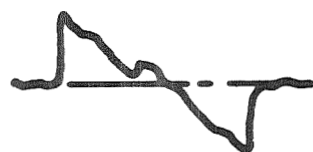
SONIC BOOM SIGNATURES

Figure 2

XB-70 aircraft were respectively roughly 100, 200, and 300 milliseconds in duration. Among people involved in sonic boom experimentation, it is the general concensus that the rounded signature shape is markedly more acceptable from a psychoacoustic standpoint than the peaked signature shape. In Figure 3, representative N wave traces are presented for the SR-71 aircraft which is capable of supersonic flight in altitudes in excess of 70,000 feet. These signatures show the increase in signature duration with increased altitude and also indicate a tendency for the initial shock wave to exhibit a finite rise time before reaching the peak overpressure. It is of interest that the trace for an altitude in excess of 70,000 feet retains the character of a finite rise time signature in spite of the long propagation path. This could be interpreted as a tendency for the signatures to reach an asymptotic form at some intermediate altitude without further advance or sharpening prior to reaching the ground.

b. Flow Field Measurements. The flow fields related to the B-58 and the XB-70 bomber aircraft have been explored by a unique experimental technique. This technique consists of flying an F-106 or F-104 probe aircraft both above and below the bomber aircraft and measuring the pressure variation at different relative positions of the two aircraft. The results of flight tests made using the XB-70 aircraft are shown in Figure 4. At the locations 2,000 feet above and below the XB-70, the flow field is observed to be closely related to the detailed geometry of the aircraft. The marked differences between the pressure field above and below the aircraft are attributed to the lift contribution of the aircraft. The probe measurements made 5,000 feet below the aircraft show the tendency for the individual waves of the flow field to coalesce at more remote distances from the aircraft. The signature length, which is in the order of two to three times the aircraft length at ground level, is observed to approach the far-field N wave shape with the exception of one intermediate shock. This intermediate shock would probably tend to coalesce with the bow shock for greater altitudes of the generating aircraft.

c. Altitude Effects. The results of experimental overflights with F-104 and F-105 aircraft during programs at Nellis AFB in 1960 and Edwards AFB in 1961 show graphically, Figure 5, the effect of increased altitude on the sonic boom signature shapes. During this program, the 120 psf overpressures were measured. These measurements and the measured overpressures of 144 psf reported in Reference 5 are probably the largest overpressures from sonic booms that have been recorded by man. The computational procedures of Carlson and Middleton (Reference 6) predict reasonably accurately the location and magnitude of the majority of the shocks in Figure 5. The atmospheric propagation for that computation was accounted for by the method of Friedman, Kane, and Sigalla, Reference 7. This

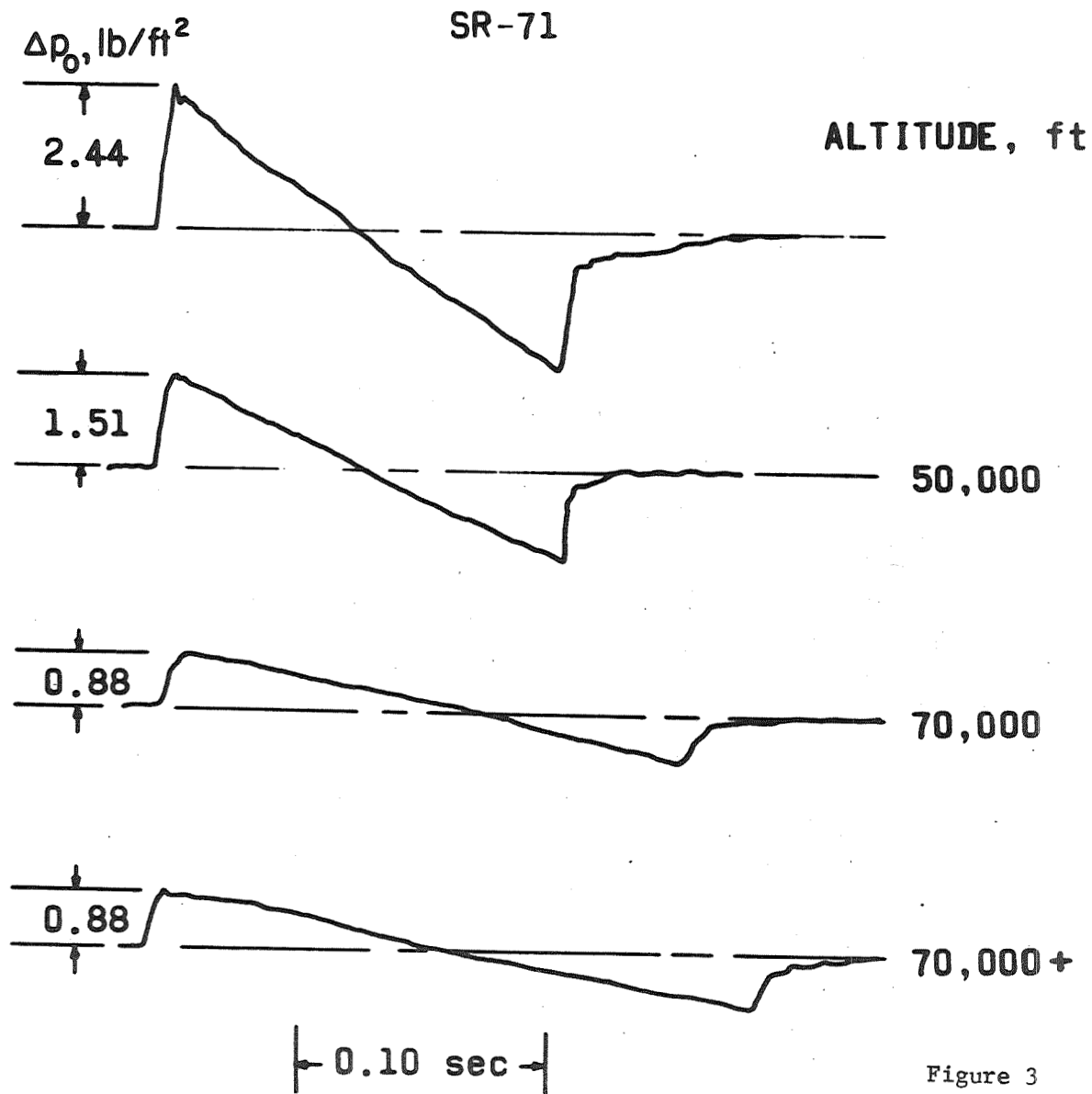# VARIATION OF SIGNATURE WITH ALTITUDE

Figure 3

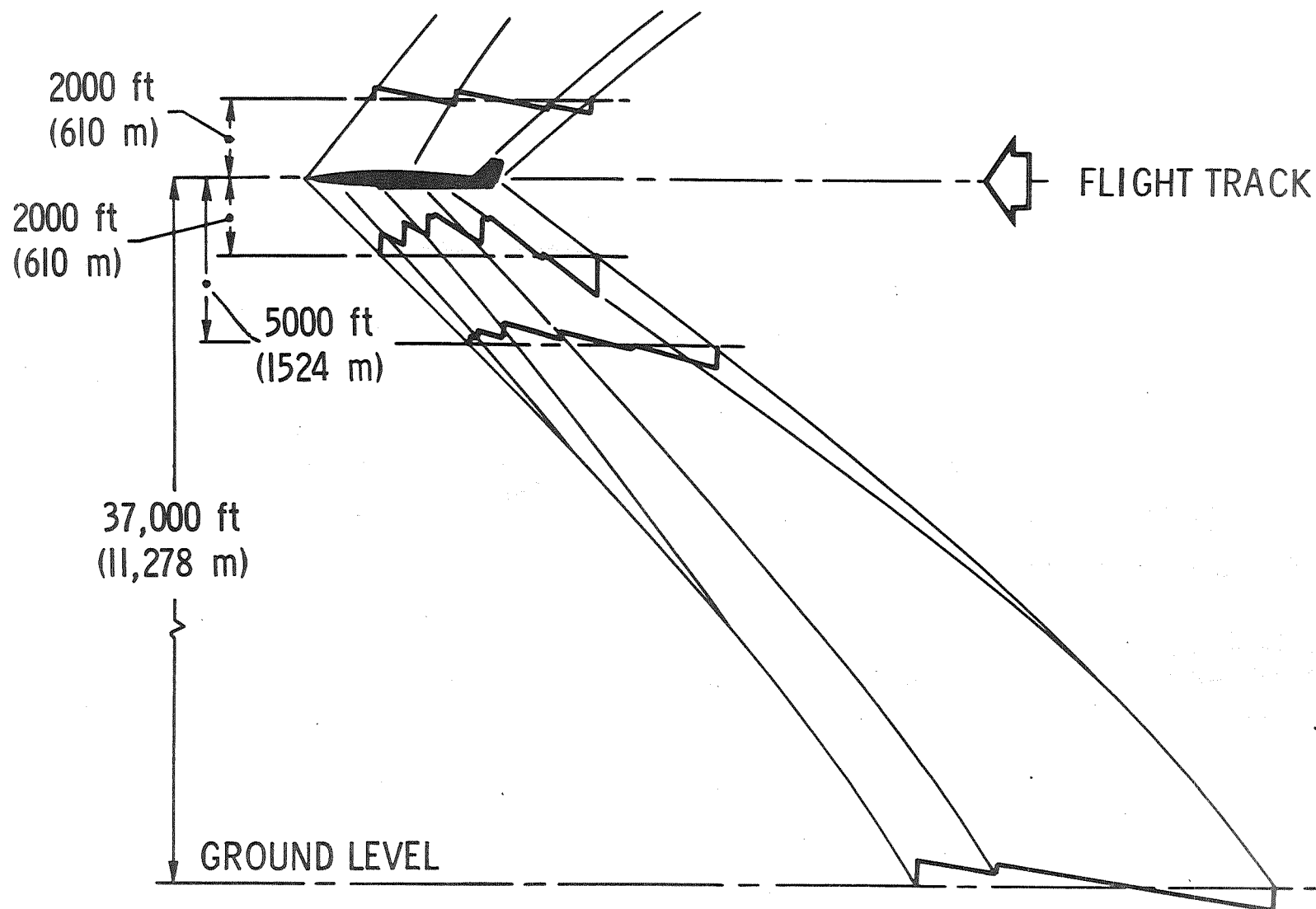# FLOW FIELD MEASUREMENTS OF LARGE AIRCRAFT

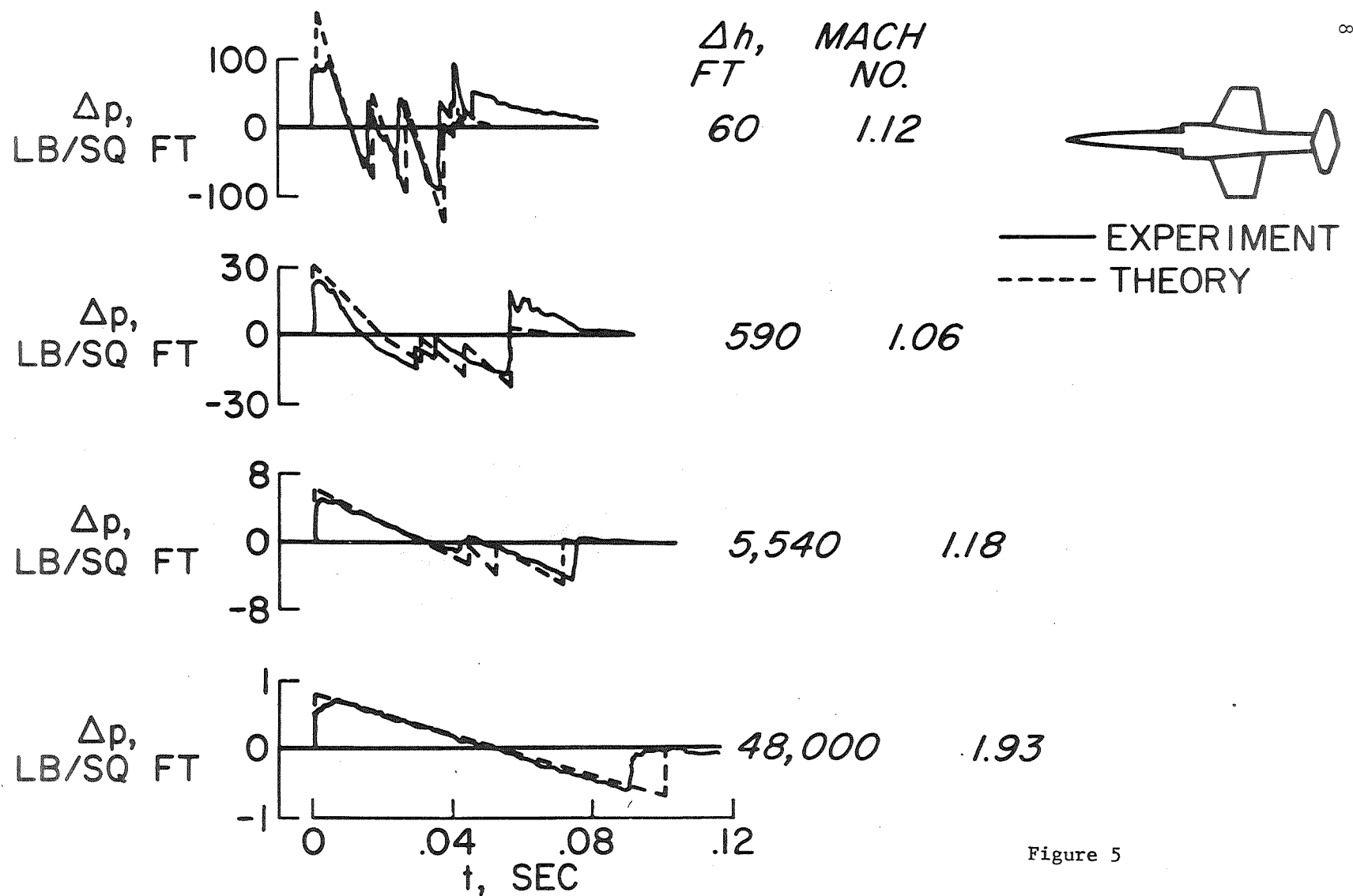Figure 4

COMPARISON OF THEORY WITH FLIGHT SIGNATURES

Figure 5

technique effectively consists of utilizing a multiplying factor
to increase the signature overpressure computed under the assump-
tion of uniform atmospheric conditions. One point to be observed
is the tendency, at the higher altitude and Mach numbers, for the
tail wave to be theoretically estimated at a location aft of the
experimentally realized value. This characteristic has been ob-
served in other calculations of high altitude or higher Mach number
results and will be discussed further in section VII. The effect
of altitude on overpressure and impulse for the B-58 and F-104
aircraft is shown in Figure 6. The comparison with the theoretically
expected altitude variation indicated on the figure shows reason-
ably good agreement with the measurements for the operational range
investigated. The increase in overpressure and impulse associated
with the larger aircraft is clearly indicated in the figure. It
is noted that these values are currently being experienced as the
result of routine military operations. A similar plot of the var-
iation of peak overpressure with altitude is presented for the
SR-71 aircraft in Figure 7. At present, the calculated sonic boom
characteristics and altitude values of this aircraft are not avail-
able to the general public. The plot does indicate, however, that
by comparison with the B-58 aircraft, which is similar in size and
weight, that no unanticipated trends were experienced. On the
figure, each symbol represents an individual mission with the solid
symbols representing the average measurements from a large number
of microphones. There is a slightly discernible trend in the meas-
urements taken during the summertime, and this variation is attrib-
uted to the less quiescent atmospheric conditions that exist at
that time of the year.

d. Lateral spread. The prediction of the spread of the sonic boom
carpet is generally well defined and the procedures have been ex-
perimentally confirmed. As a rough rule of thumb, the total lat-
eral spread in miles may be related to the aircraft altitude in
thousands of feet. For example, in Figure 8 the lateral spread
of the B-70 sonic boom track when generated at altitudes of 37
and 60,000 feet is roughly in the order of 35 and 60 miles re-
spectively. While the character of the lateral spread is well
predicted, it is seen that there is some difficulty in predicting
the actual point of lateral cut-off. This characteristic is ob-
served again in Figure 9 for flights of the SR-71 aircraft. In
Figure 10, the actual signature traces at varying lateral distances
from the ground track are given for the SR-71 aircraft at an alti-
tude in excess of 70,000 feet. It is seen that as the distance
from the flight track increases, the signatures tend to become
rounded with an increased rise time. At the distance of 26.8 n.mi.
from the flight track, which is very near to lateral cut-off, the
sonic boom signature tends to degenerate into an approximate sine wave.

COMPARISON OF THEORETICAL AND FLIGHT DATA
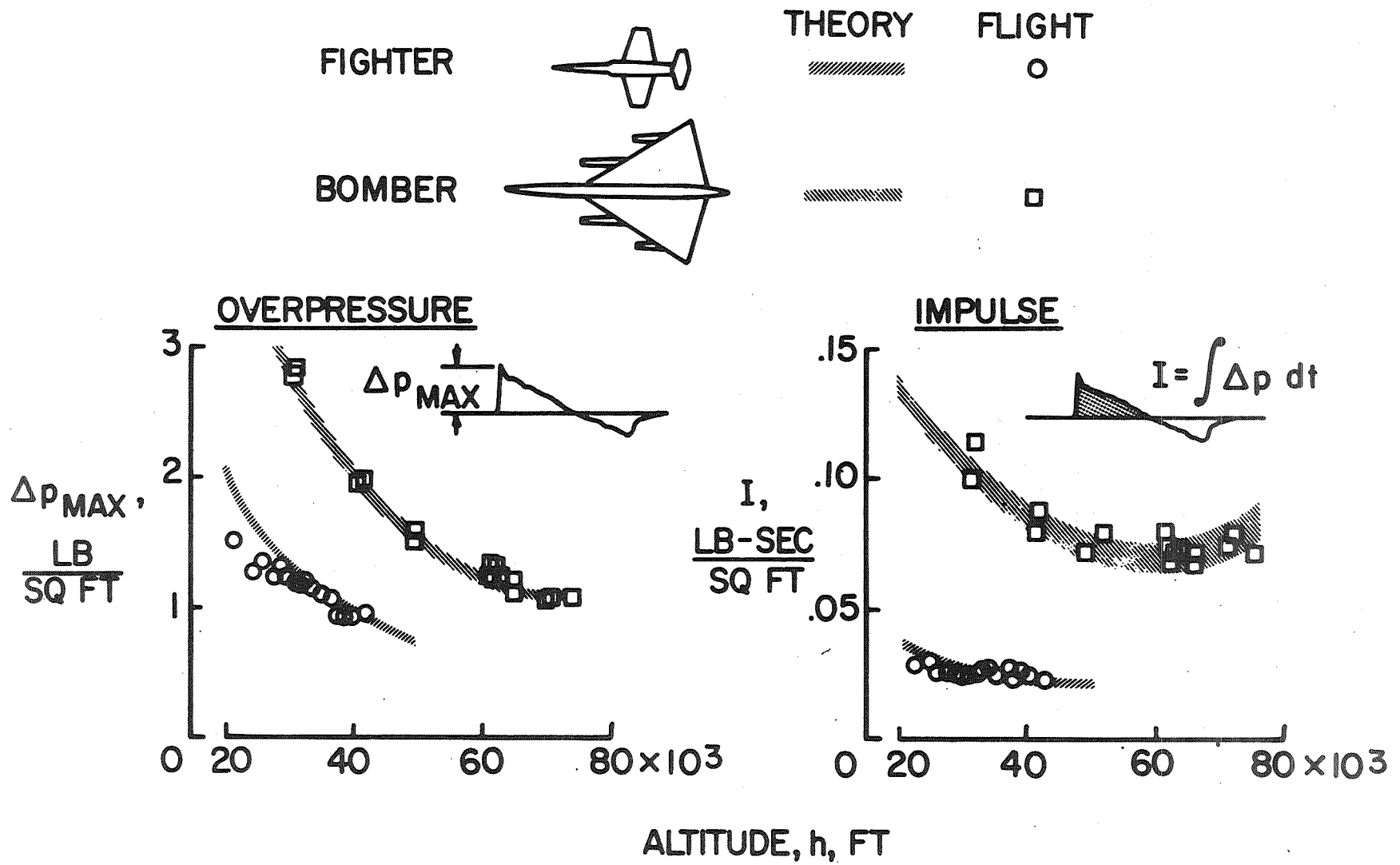
Figure 6

SR-71 GROUND TRACK OVERPRESSURES

● 20 to 64 MIKES (WINTER DATA)

○ 3 to 5 MIKES (WINTER DATA)

◆ 20 to 64 MIKES (SUMMER DATA)

CALC. AND MEAS. B-58 FROM REF. 6

Δp_o
lb/ft^2

28 FLIGHTS
928 DATA SAMPLES

ALTITUDE

Figure 7

LATERAL SPREAD PATTERNS
XB-70

Figure 8

SR-71 LATERAL SPREAD OVERPRESSURE
EAFB

(a) M = 2.0 @ 50,000' (2 FLTS)

(b) M = 3.0 @ 70,000'+ (15 FLTS)

Figure 9

VARIATION OF SIGNATURE WITH LATERAL DISTANCE

SR-71   M=3.0 @ 70,000'+

Δp_0, lb/ft^2

LATERAL DISTANCE, n.mi.

1.12

0.09

0.81

10.1

0.66

19.4

0.16

26.8

$\vdash$ 0.10 sec $\dashv$

Figure 10

e. <u>Wavefront Ground Intersection</u>. The data presented in the pre-
    vious section on the lateral spread of the overpressures has been
    time correlated utilizing radar tracking data to define airplane
    position. From the time correlation of the measurements it was
    then possible to define the shockwave ground intersection shown
    in Figure 11. As was anticipated, the intersection of the air-
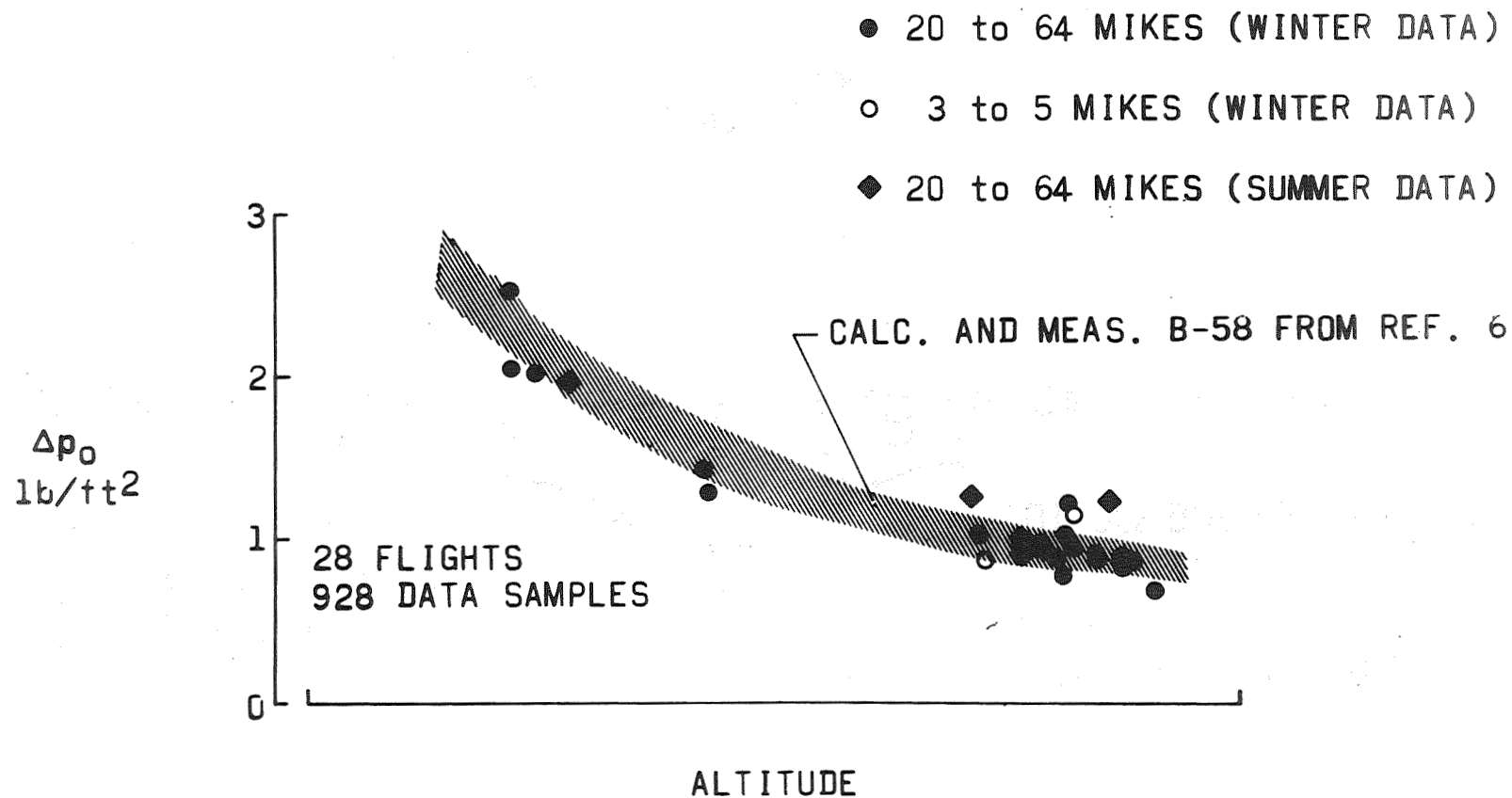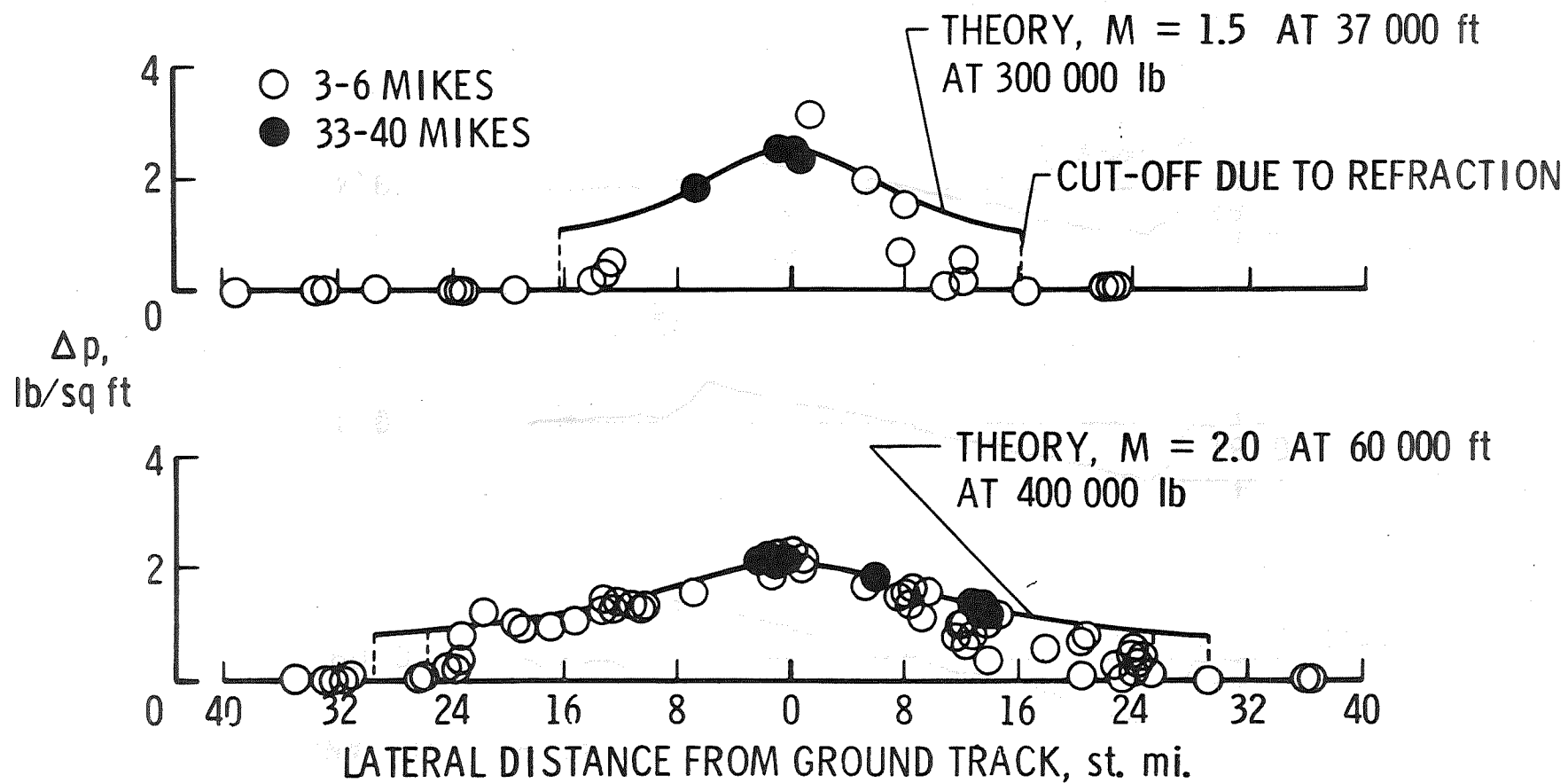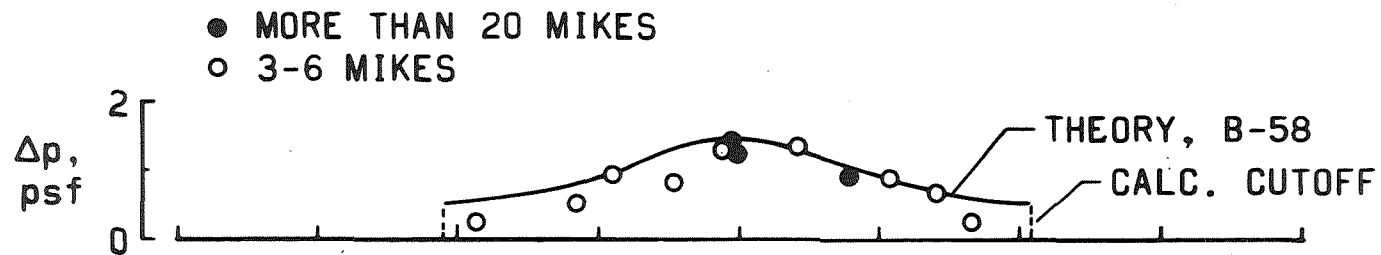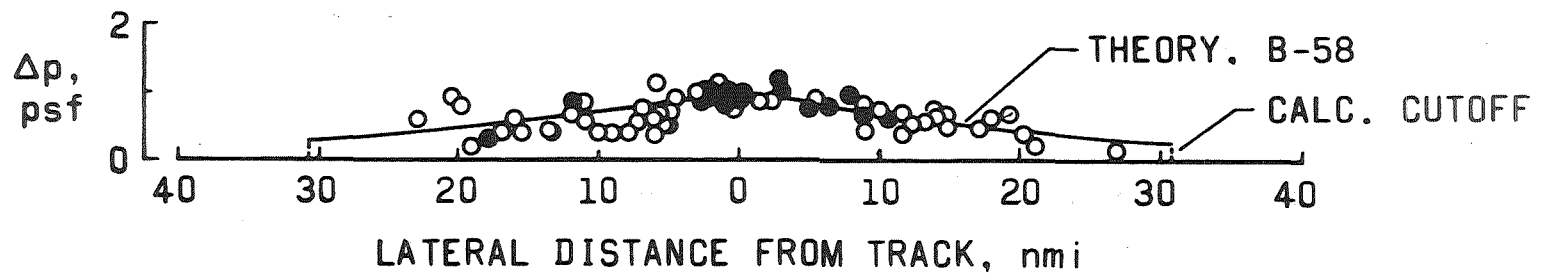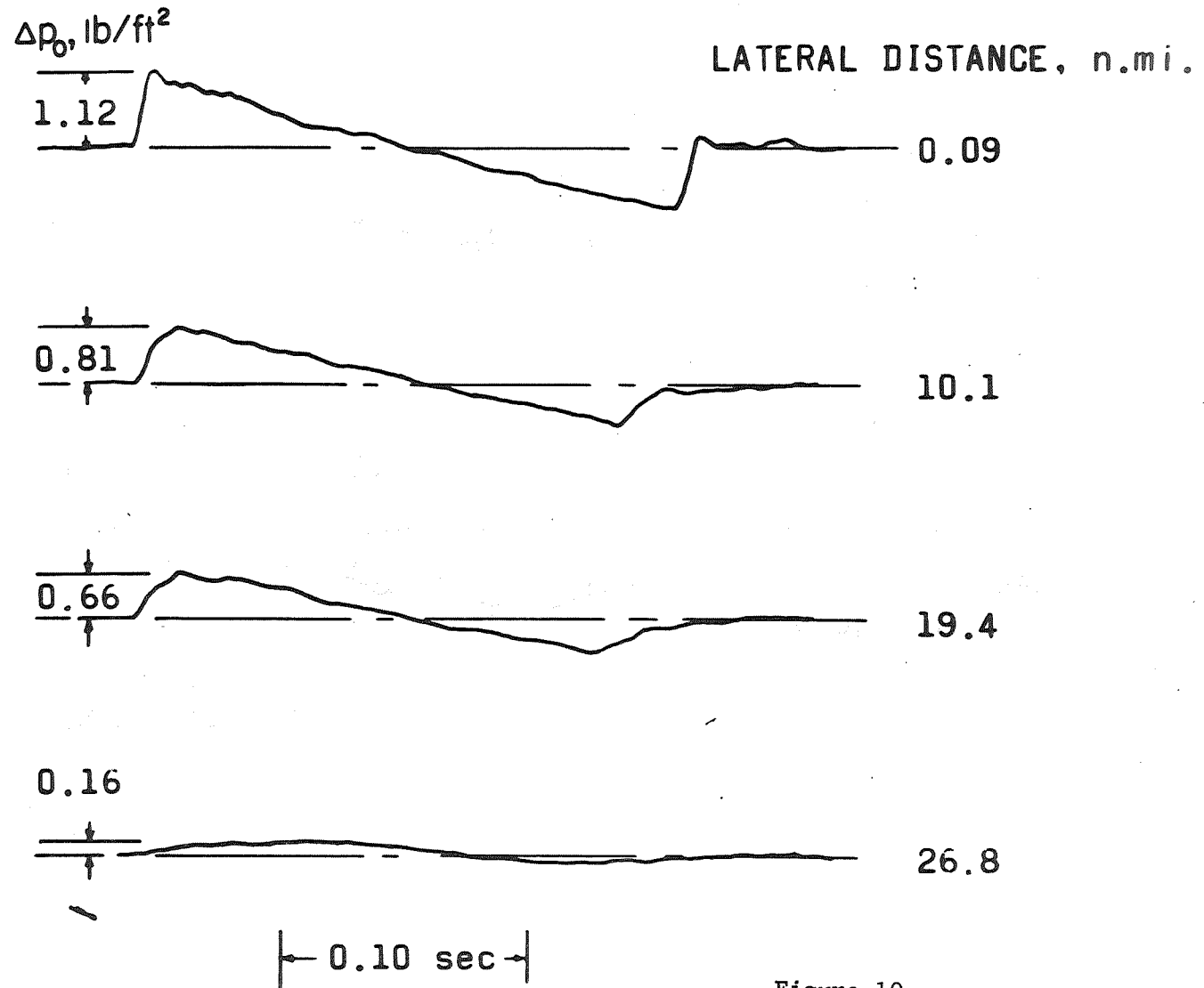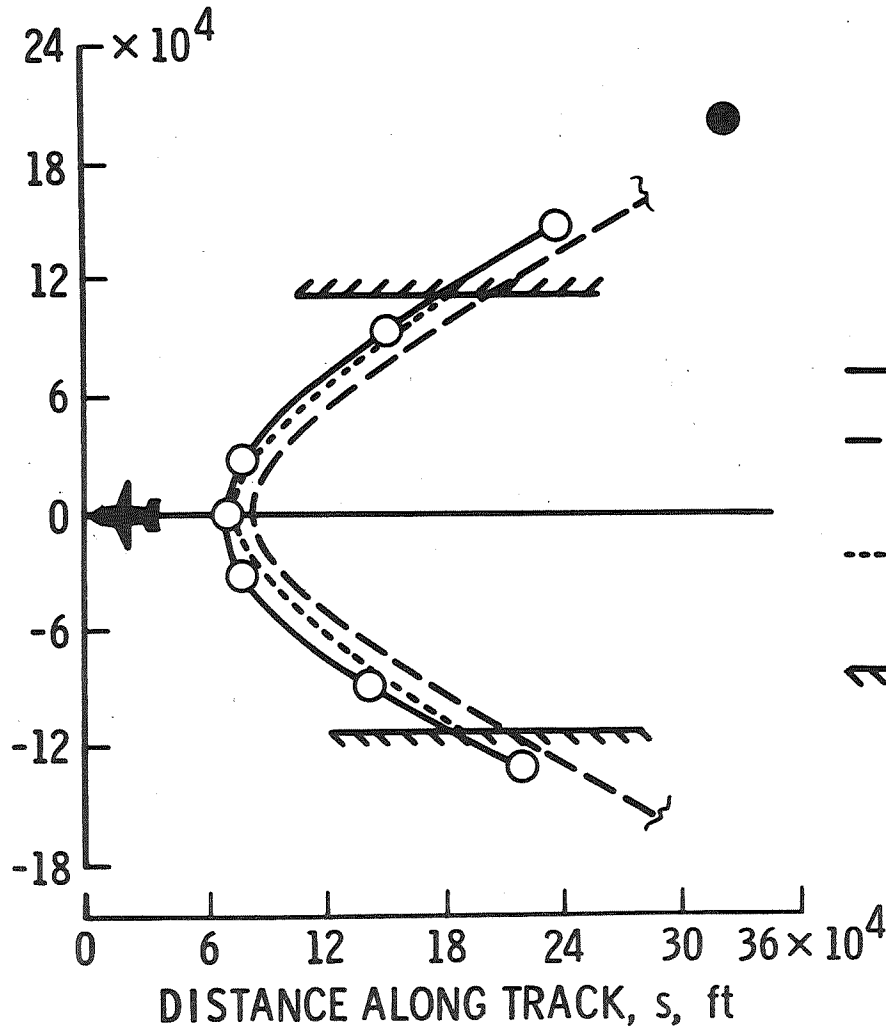   craft's Mach cone with the ground approximately forms a hyperbola.
    Using the calculation method of Reference 8, ground intersections
    were estimated using both a homogeneous and the actual atmosphere.
    The calculations utilizing the homogeneous atmosphere tend to
    intersect the ground track three to four miles behind the calcu-
    lations made with the actual atmosphere. This is attributed to
    the lack of refraction of the acoustic ray paths in the absence
    of atmospheric temperature gradients. The agreement with the
    calculations using the actual atmosphere and the experimental
    data is considered to be quite satisfactory. It is interesting
    to note that the aircraft is approximately 20 miles beyond the
    point on the ground at which the boom is observed.

f. <u>Atmospheric Effects</u>. Investigations of the atmospheric effects
    on sonic boom signatures are considered of primary current import-
    ance. Accordingly, in the present meeting, a paper by Angell,
    Herbert, and Hass (Reference 9) will explore this subject in some
    depth. It is, however, considered desirable in the present survey
    to include for completeness some representative results which were
    significant in pointing up the importance of the problem of sonic
    boom atmospheric interactions. The pressure signatures presented
    in Figure 12 were measured by flights over a linear microphone ar-
    ray with microphones spaced at 200 foot intervals. The recorded
    waveforms in the distance of the 800 foot array vary from sharply
    peaked signatures to extremely rounded signatures with maximum
    overpressures differing . by a factor as great as three. Since
    these measurements were taken under moderately turbulent atmos-
    pheric conditions, it was hypothesized that the rapid signature
    variation was associated with inhomogeneities in the atmosphere.
    To isolate the segments of the atmosphere which contributed to
    the distortion of the sonic boom signature, measurements were made
    by the technique indicated on Figure 13. The "blimp," which had
    a microphone mounted in a manner to minimize interference with the
    sonic boom measurements, was flown at altitudes up to 2,000 feet.
    Accordingly, it was able to penetrate fairly deeply into the upper
    reaches of the earth's boundary layer and sonic boom signatures
    were measured which had passed only through a small segment of
    the earth's boundary layer. The incident shockwaves were often
    observed to be sharp, undistorted N waves whereas the reflected
    shocks which traversed the earth's boundary layer to the ground
    and returned to the blimp were considerably distorted. These
    measurements tend to indicate that the majority of the distortion
    occurs in the lower altitude turbulent air masses even though on

BOW SHOCK WAVE GROUND INTERSECTION PATTERNS

Figure 11

EFFECT OF ATMOSPHERE ON PRESSURE SIGNATURE

Figure 12

AIRSHIP MEASUREMENTS

F-106 AT M = 1.5

INCIDENT SHOCKS

REFLECTED SHOCKS

40,000 ft
(12.2 km)

BLIMP

2000 ft
(610 m)

MICROPHONE

GROUND LEVEL
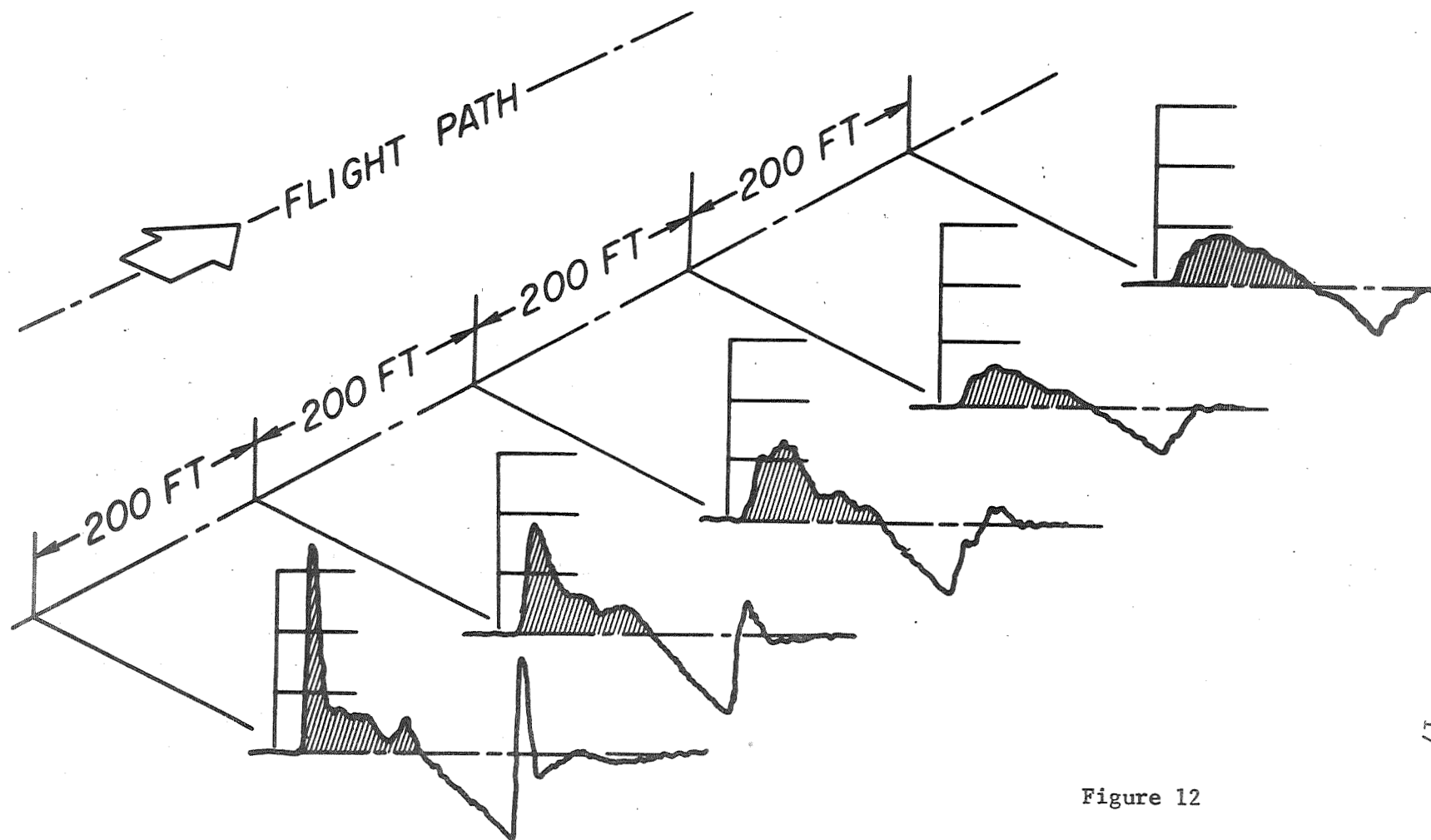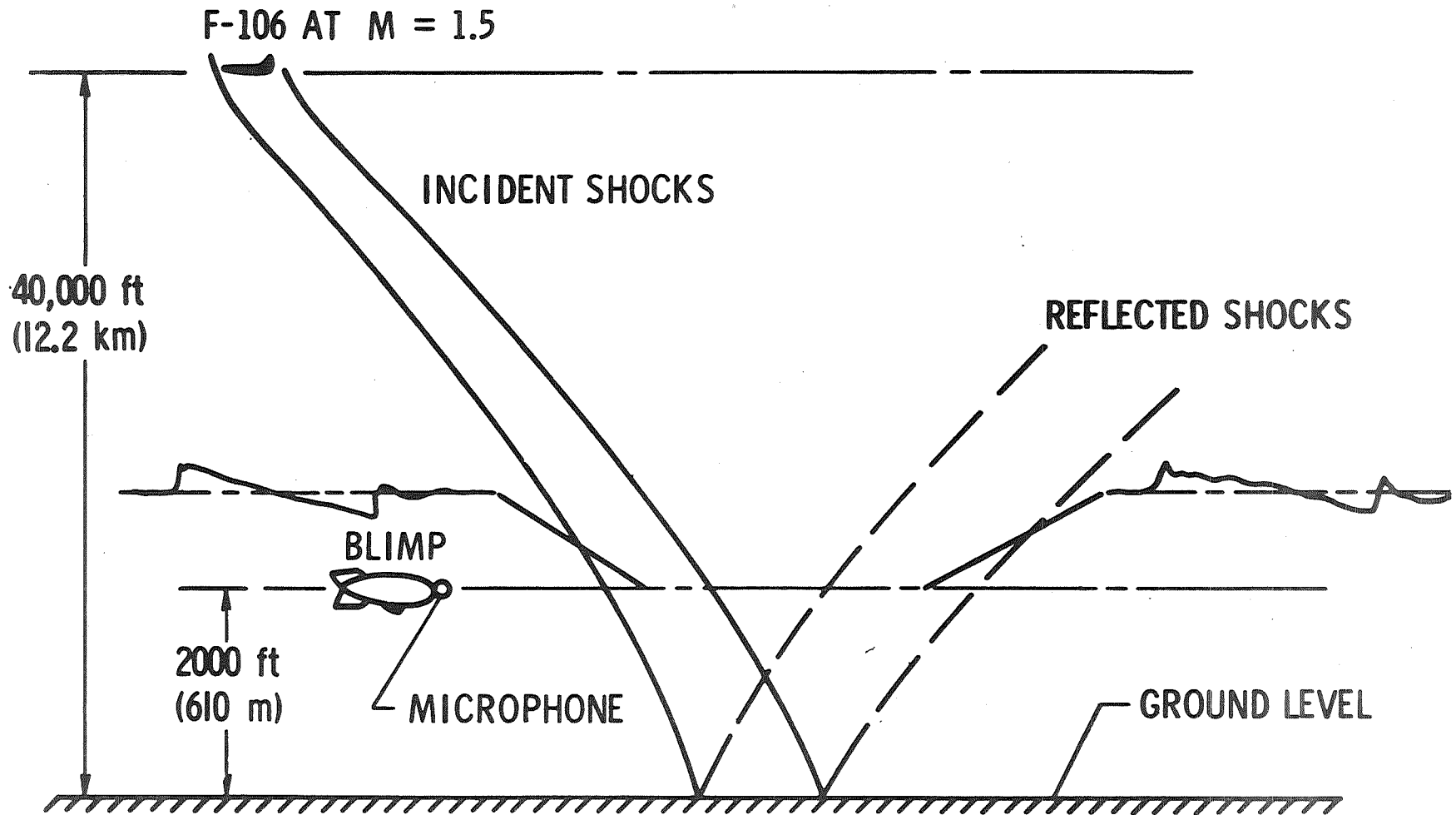
Figure 13

occasions the incident waves at the blimp level did indicate some distortion. A recent scattering mechanism has been proposed by Crow (Reference 10) which offers great potential in defining the mechanism of sonic boom atmospheric interaction. However, further experimentation is believed to be necessary to quantitatively substantiate the scattering theory.

g. <u>Aircraft Maneuvers</u>. The subject of amplification of sonic boom overpressures due to aircraft maneuvers has been investigated for many years. Attempts have been made to measure the maneuver amplification factors for turning maneuvers, linear accelerations, and porpoising maneuvers. The very excellent experimental work of the French in projects "Focalization" and "Jericho" and the procedures developed by Guireaud are described in the present conference (References 11 and 12). In an early Edwards AFB test program, a series of linear accelerating maneuvers was made and the experimental overpressure measurements taken along the ground track are shown in Figure 14. In this figure, the results from three independent flights have been normalized to the zero distance along the ground track. As noted on the schematic sketches, the ground zero point occurs at the location where the superboom first touches the ground. Further down the track, the sonic boom separates into two separate shock waves with the trailing shock resulting in weaker overpressures because it was generated at an earlier point in time and hence experienced more distance attenuation. In this series of accelerated flights, the maximum amplification of the sonic boom overpressure was approximately three times the value of the unamplified sonic boom. It is interesting to note that acoustic ray tracing techniques have been utilized to predict the location of the superboom and have, in many cases, been accurate within three miles.

A second motion of the aircraft, namely, a porpoising flight, was studied to determine if this type of motion could be a contributor to the variation of signatures along a linear ray as indicated in Figure 12. In this test, a series of flights at an altitude of 35,000 feet and Mach number of 1.5 were made with an F-106 aircraft. As is shown in Figure 15, the motion of the aircraft produced a plus and minus 0.5g normal acceleration. The period of the motion was one second which corresponds to wave lengths of approximately 1600 feet. Attempts were made to correlate the experimental overpressure variations with the wave length of the aircraft motion to see if the perturbations about the flight track resulted in corresponding shockwave perturbations which would be propagated to the ground. It was not possible from this data to obtain correlations with any preferred wave length. When the root mean square overpressure difference was plotted as a function of separation distances between two measuring microphones, it was found that the data for steady and porpoising overflights essentially coincided.
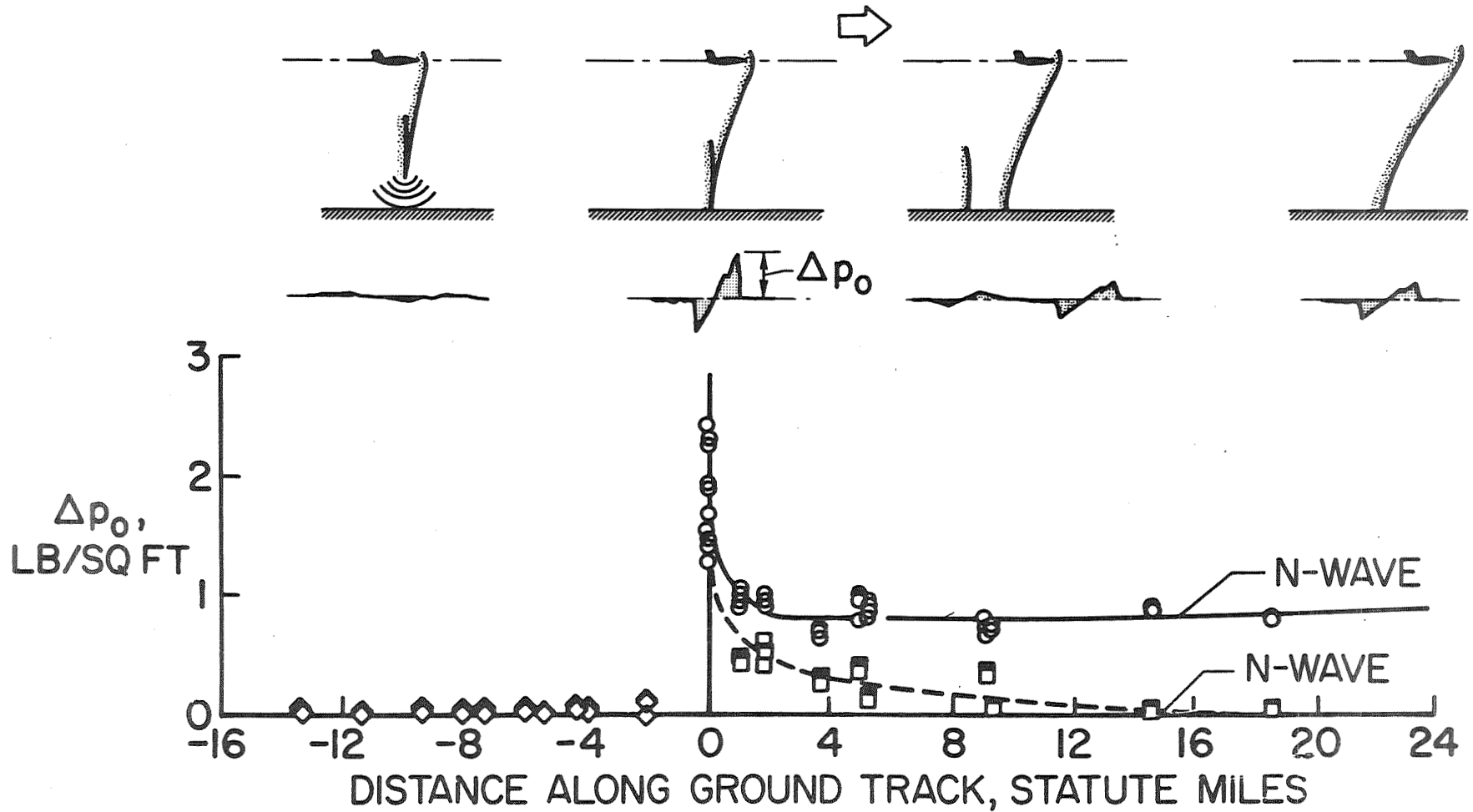
GROUND PRESSURES FOR ACCELERATED FLIGHT

Figure 14

SETUP FOR STUDYING AIRPLANE MOTION EFFECTS

$M = 1.5$

$\pm 0.5g$

1 sec

$M = 1.5$

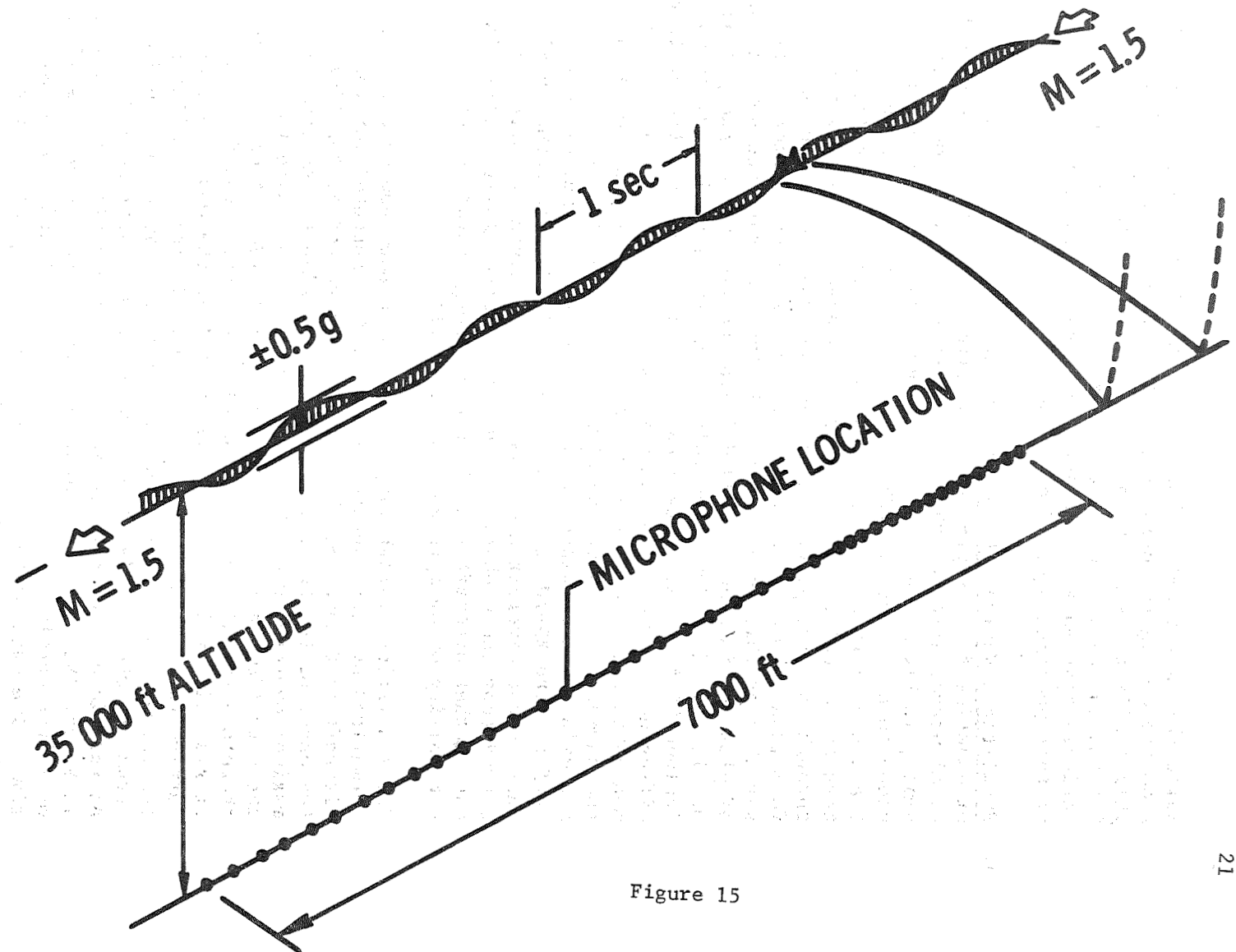MICROPHONE LOCATION

$M = 1.5$

35 000 ft ALTITUDE

7000 ft

Figure 15

While this might imply that variations of the overpressure made from these flights could be essentially contributed to atmospheric effects, some recent computations indicate that the variations may be due to the porpoising motion. Accordingly, it is believed that more theoretical and experimental investigations of this phenomenon would be desirable.

h. <u>Statistical Variability of Peak Overpressures</u>. The large number of experimental overpressure measurements facilitates the statistical presentation of the peak overpressure variation. For example, in Figure 16, measurements made on the XB-70 aircraft are shown on a log normal probability plot. Otherwise expressed, the probability of the measured value exceeding or being less than the calculated overpressure is presented. A straight line through the data points indicates that the overpressures measured form logarithmically a normal or Gaussian distribution. Also observable on this type of a plot is the fact that the variations of plus or minus one standard deviation lie between the probability of .16 and .84. Extending this to two standard deviations would include 95.5% of all data presented. In Figure 16, the striking difference between data taken in the summertime and in the winter months is indicated. A much greater variability is noted during the summer months when the atmosphere is inclined to be less stable. A similar plot of wintertime variability for three different aircrafts, (the XB-70, the B-58, and the F-104), is shown in Figure 17. While these aircraft are considerably different in size, it is observed that the probability curves are essentially similar indicating that aircraft size is not a strong factor in the statistical variability of overpressure measurements.

The statistical variability of the sonic boom bow wave rise time normalized by peak overpressure value is presented for the SR-71 aircraft in Figure 18. Rise time was measured as the time from the onset of the bow shock overpressure rise to the time of the maximum overpressure. The overpressure values used to normalize the rise time data were generally on the order of one psf and therefore the histogram essentially represents the distribution of rise time values. It is observed that the most frequently occurring value of the rise time is approximately 10 milliseconds. The longer rise time values were associated with the rounded wave forms and shorter rise times are associated with peaked wave forms. An additional presentation of the normalized rise time is presented in Figure 19. This presentation attempts to explore the effects of flight conditions or specifically of altitude on the SR-71 rise time. The data symbols represent the average of a large number of flights taken within ± 3 n.mi. of the ground track and the vertical extent of the lines indicates the scatter in the experimental data. While it is difficult to specify absolute trends from data with such large scatter, it is possible to observe that there is a tendency for the rise time to be larger at the higher altitudes. A

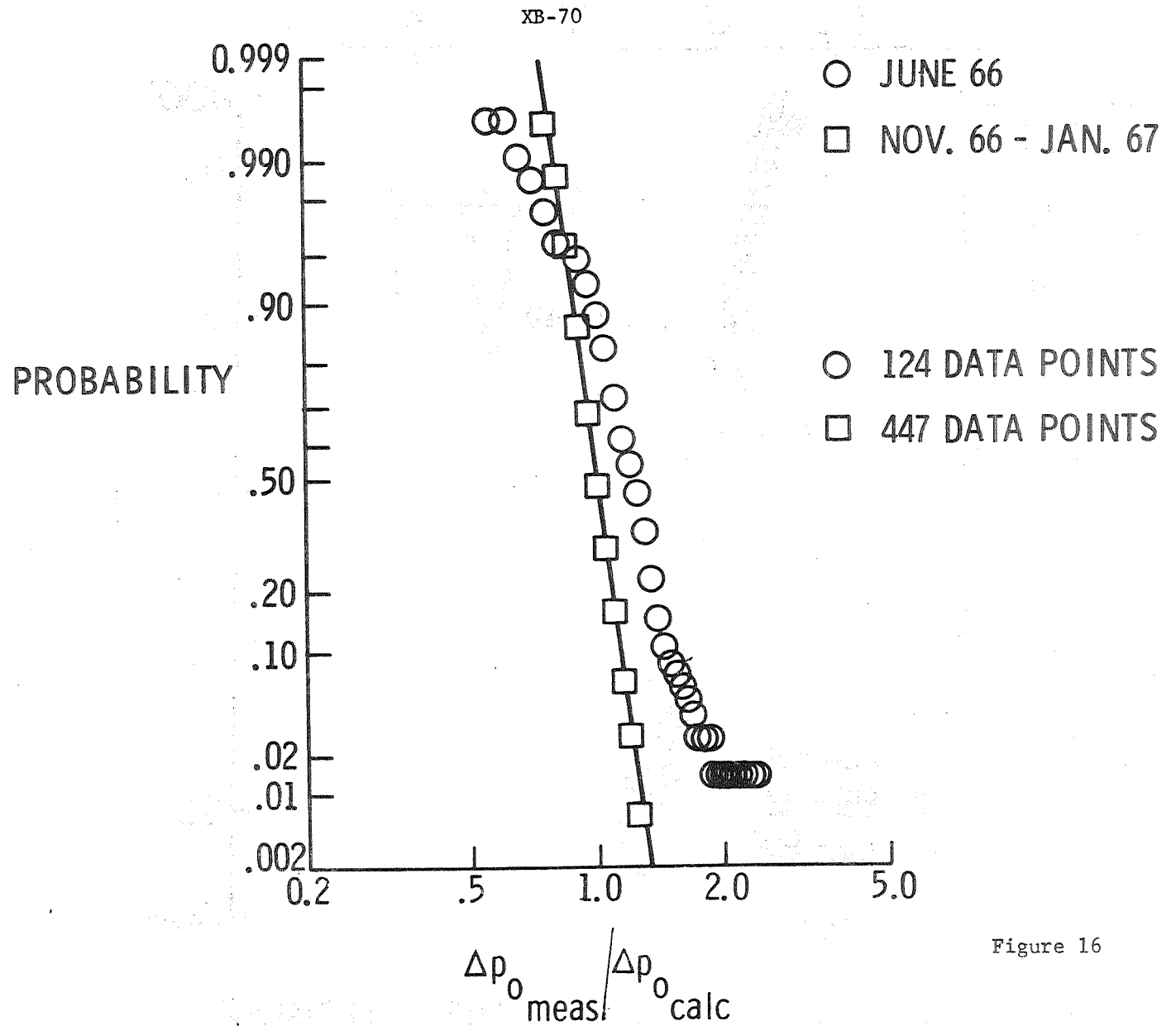# PROBABILITY DISTRIBUTIONS

XB-70

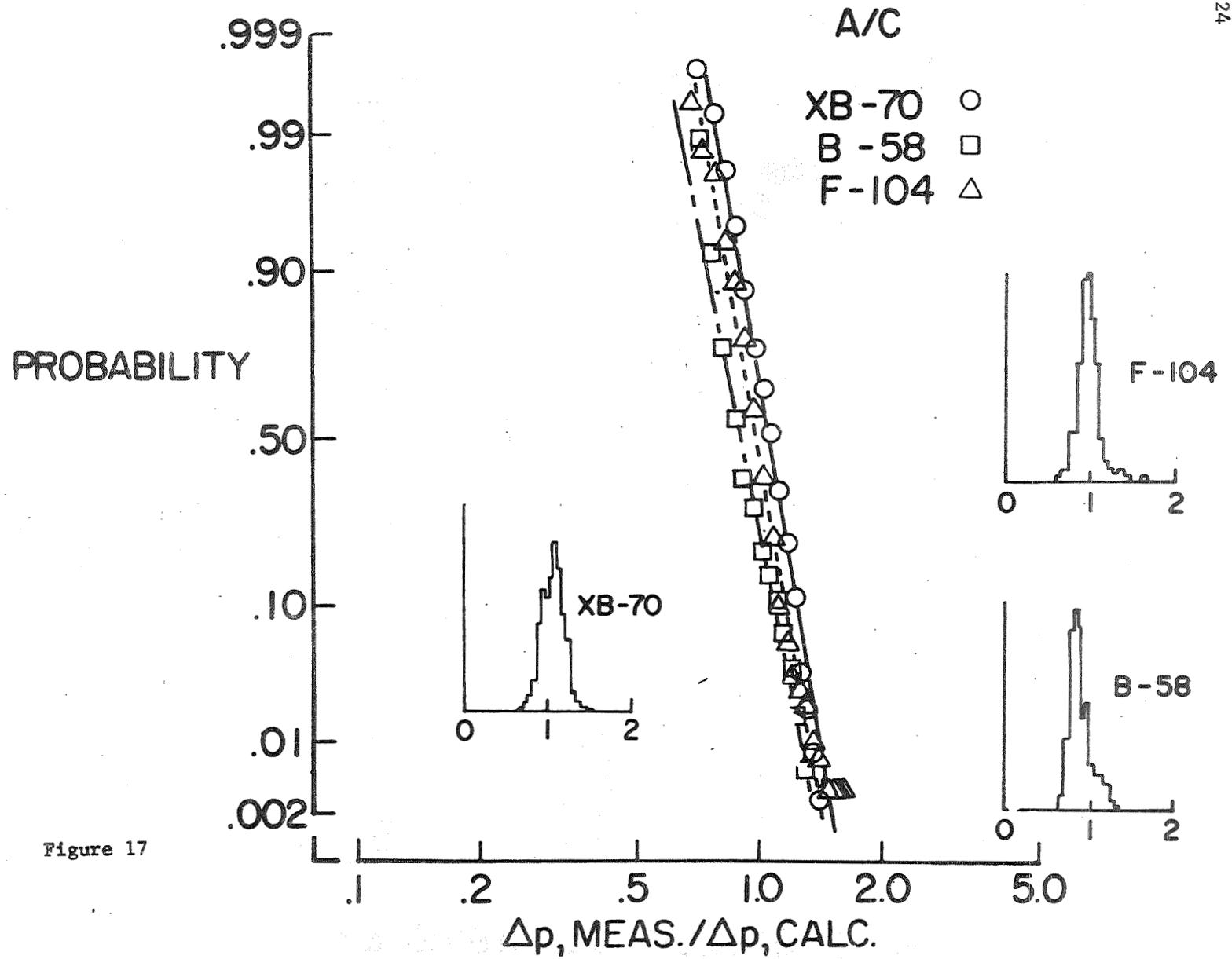Figure 16

PROBABILITY DATA FOR THREE AIRCRAFT

Figure 17

VARIATION OF RISE TIMES

SR-71 M=3.0 @ 70,000'+

680 DATA SAMPLES
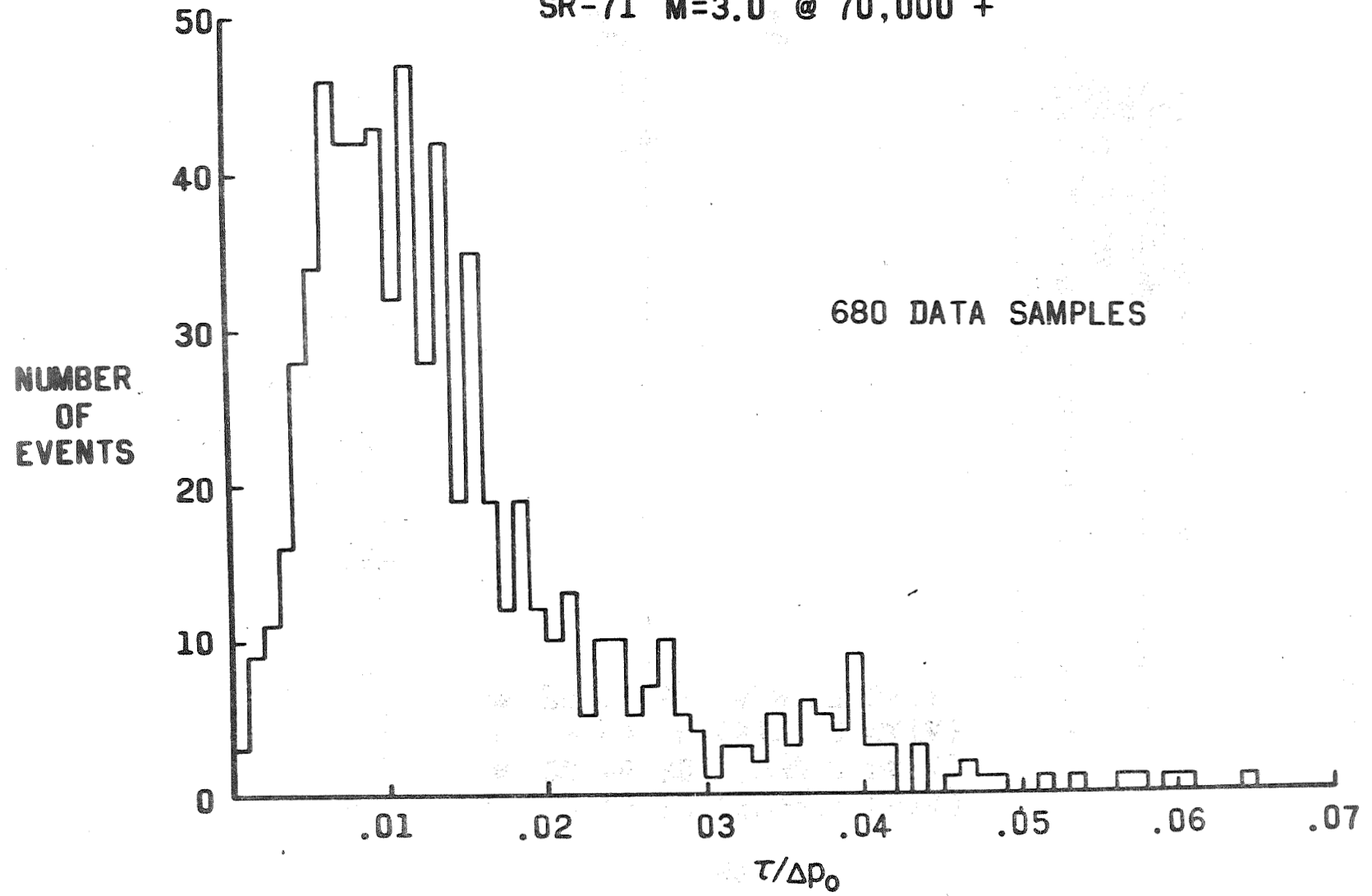
NUMBER OF EVENTS

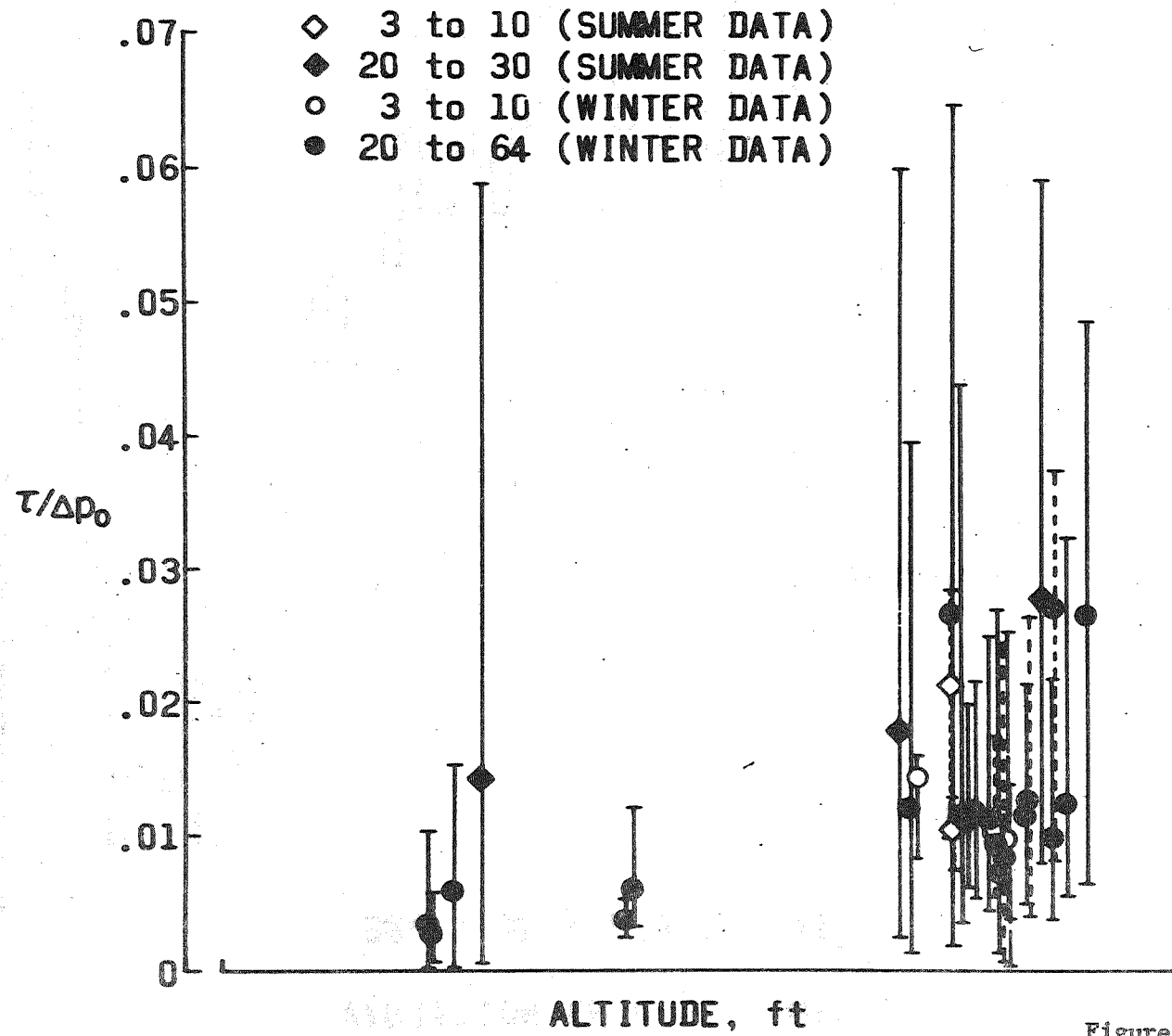$\tau/\Delta p_o$

Figure 18

EFFECTS OF ALTITUDE

SR-71

Figure 19

possible explanation of this trend may be related to the development of the age variable of the signal and its approach to an asymptotic limit but a more probable explanation is related to atmospheric effects. Beyond the asymptotic limit, further sharpening of the signature is not probable and correspondingly, atmospheric scattering may effectively thicken the shock front. Irrespective of the cause, the tendency for the SR-71 aircraft to produce signatures with a finite rise time continues to be demonstrated by recent overflight measurements made in Pendleton, Oregon. Since increased rise time is considered to be a favorable characteristic from subjective response considerations, these data will be examined in detail to explore the parameters contributing to this favorable signature characteristic.

IV. SONIC BOOM EFFECTS ON ENVIRONMENT

Since the sonic boom is a rapid transient pressure pulse, it is apparent that it may have the potential of producing adverse physical and psychological effects on people, animals, and structures. Accordingly, a large number of the overflight studies were directed at evaluating these potential effects and at attempting to quantitatively relate the magnitudes of structural and psychoacoustic interactions to the characteristics of sonic boom signatures. The tests previously mentioned to evaluate the feasibility of using the sonic boom as a weapon produced essentially negative results and the balance of the overflight testing was directed at the general acceptability of overland supersonic flight in terms of psychoacoustic reactions and potential structural damage.

a. Structural Effects. The character of the transient structural loading is indicated in Figure 20. The aircraft is approaching the building from left to right and initially there is a racking load followed by a period during which the positive pressure pulse engulfs the building. This inward pressure loading is quickly reversed as the negative portion of the pressure pulse passes over the building and then finally as the tailwave passes the building receives a second racking load. The response of a building to a typical sonic boom stimuli is shown in Figure 21. The sonic boom signature illustrated in this figure is of the "spikey" character with the peak overpressure just slightly under 1.5 psf and a duration of approximately 100 milliseconds. From the measurements made inside of the house, it is observed that the overpressure levels are considerably reduced and that the wave form is markedly altered. The curve labeled "Noise" represents measurements made with a filter which passed acoustic signals in the audible range. The amplitude of this signal is an order of magnitude lower than the internal pressure pulse. A lower curve labled "acceleration" indicates the vibrations of the floor which would be sensed directly or through the furniture in the room. This characteristic is a direct response to both the outside pressure pulse and the inside pressure oscillations. Because of the comparatively favorable

SEQUENCE OF LOADING
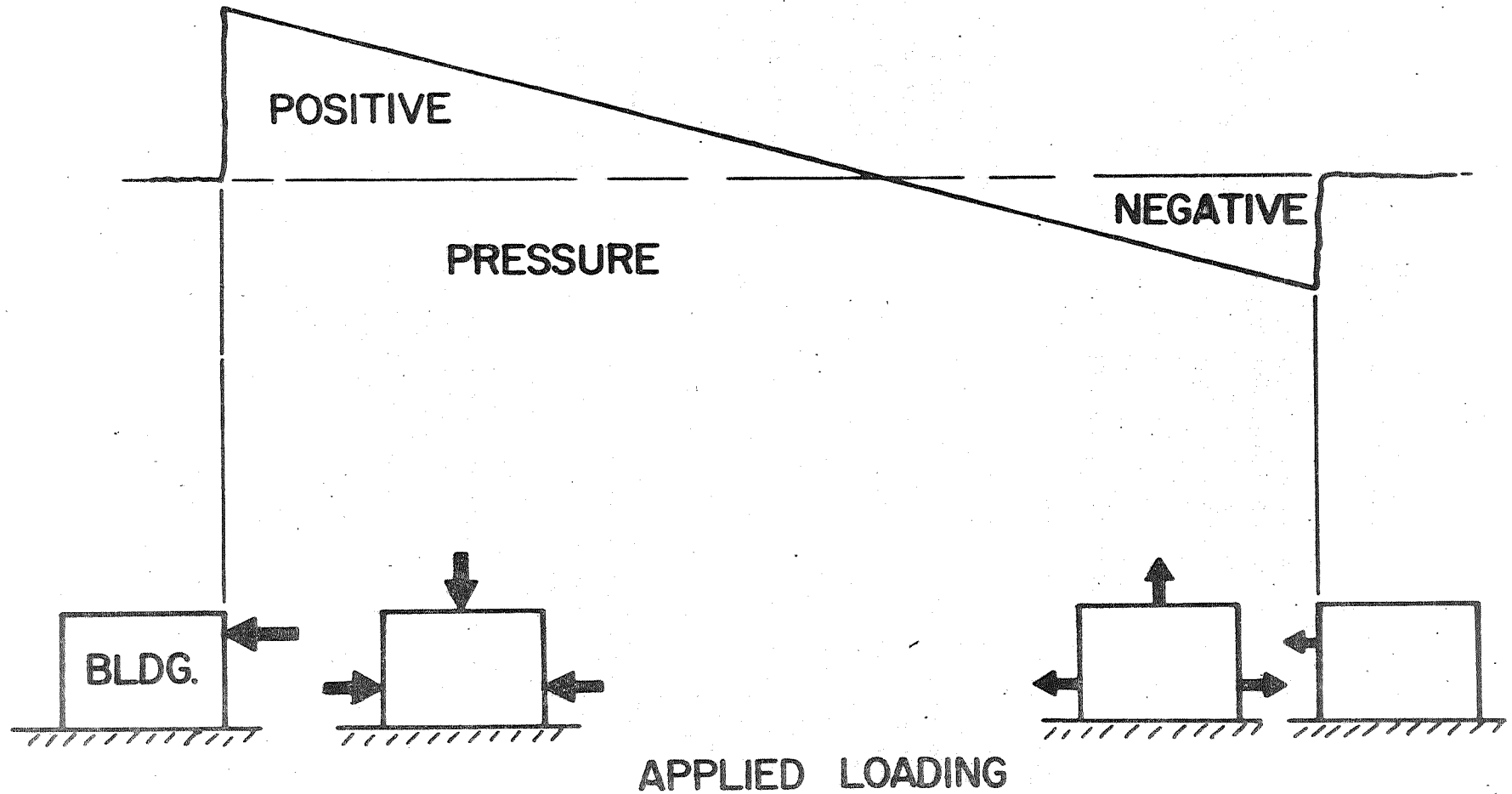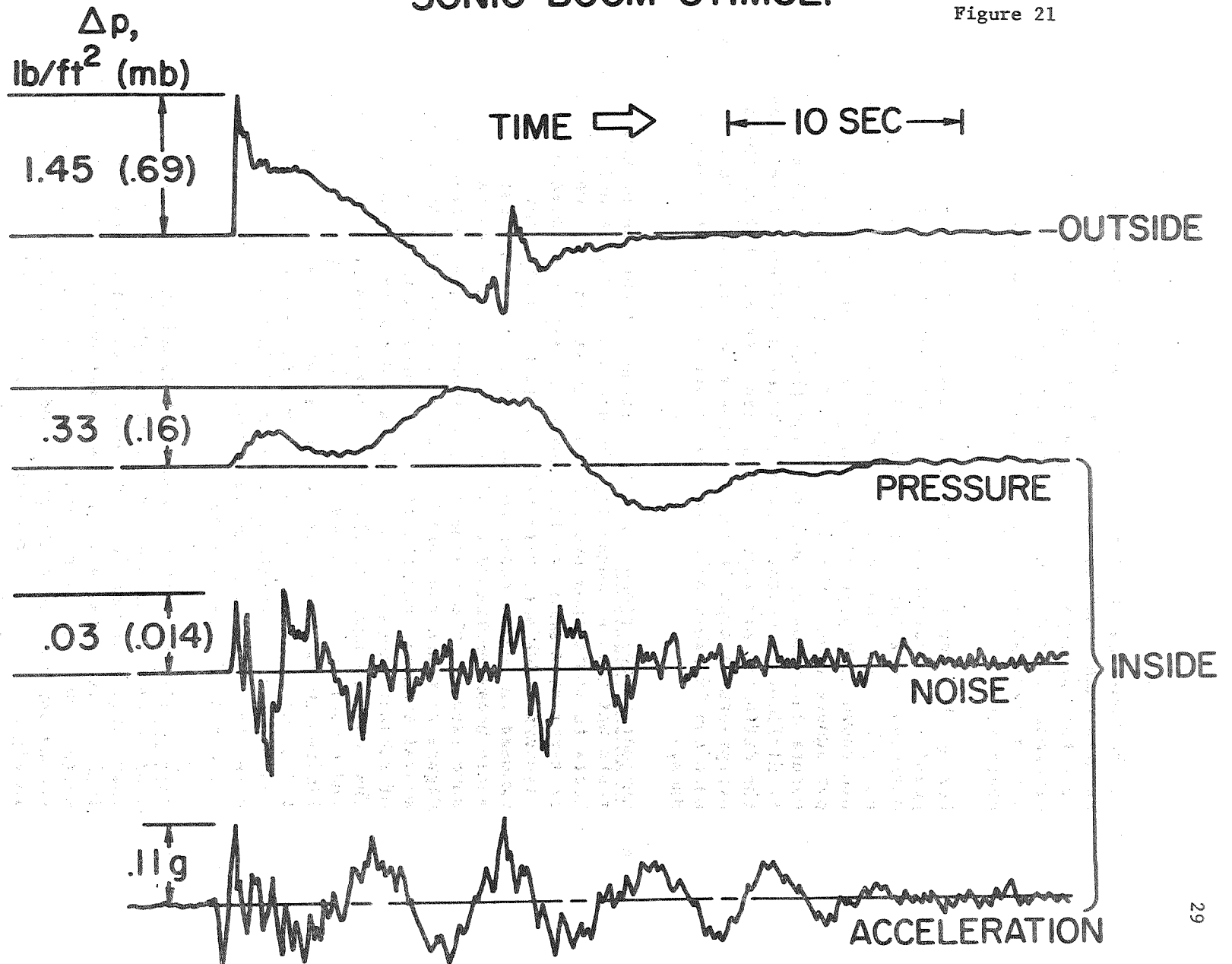

POSITIVE

NEGATIVE

PRESSURE

BLDG.

APPLIED LOADING

Figure 20

SONIC BOOM STIMULI

Figure 21

Δp, lb/ft^2 (mb)

TIME ⟹   ⊢— 10 SEC —⊣

1.45 (.69)

OUTSIDE

.33 (.16)

PRESSURE

.03 (.0|4)

NOISE

INSIDE

.11 g

ACCELERATION

29

psychoacoustical evaluation of finite rise time sonic boom signatures when heard outdoors, it is considered desirable to evaluate the response of building structures to these signatures to determine if the structural characteristics of the building offset the desirable characteristics of the signature on the indoor observers.

During the overflight program at Edwards Air Force Base, it was possible to evaluate the effects of sonic booms of considerably different duration on the acceleration of walls of one- and two-story houses. The results of the wall acceleration measurements are shown in Figure 22 and are given for overpressures up to 4.4 lbs. per square foot. While the three different aircraft used had signature durations of one, two, and three hundred milliseconds, it is difficult from the figure to discern difference responses for the different aircraft. It is also observed that at the maximum overpressures experienced in these tests, the wall accelerations were considerably below the value set as a criteria for structural damage.

b. Subjective Reactions. A major feature of the recent Edwards AFB tests was that of measuring the psychoacoustic reactions of subjects to sonic boom overflights. These reactions were evaluated in terms of a more familiar noise; namely, the noise of aircraft flyovers. Subjects were selected from nearby communities and were exposed in random order to pairs of subsonic aircraft flyovers and sonic booms generated by different aircraft at different overpressure levels. The evaluated experimental data is presented in Figure 23 where the large shaded area represents not only experimental scatter, but the difference between the subjective reactions of subjects located inside houses and subjects located out-of-doors. The lower boundary of the shaded region was generally related to indoor subjective response. This type of comparison is somewhat limited in value because weighting factors with respect to durations and pure tones of the flyover noise were not included and the sonic boom signatures were not weighted in terms of signature rise time which is known to result in a relative reduction of the sonic boom annoyance level.

c. Seismic Effects. It has been postulated that the effects of the sonic boom on ground-induced motion might be an area for concern. Accordingly, ground-induced motions resulting from overflights by fighter and bomber aircraft have been measured in terms of the three components of the ground acceleration. Measurement of the ground particle velocity presented as a function of time is given in Figure 24. This pressure wave resulted from the sonic boom produced by a B-58 aircraft and the theoretically anticipated values are indicated by the dashed curve. The highest values of the particle velocity are associated with the passage of the bow

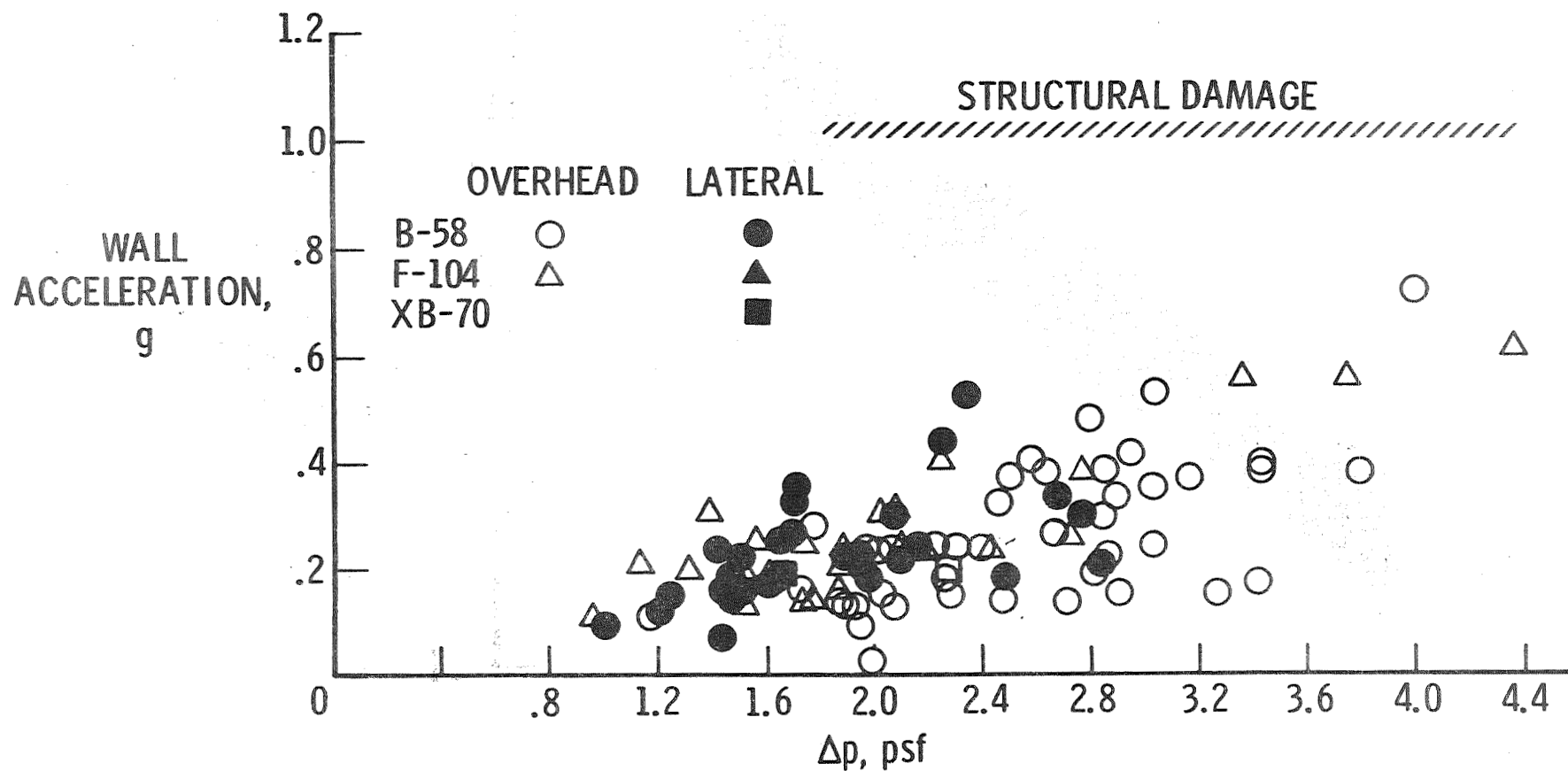BUILDING WALL VIBRATION AMPLITUDE AS A FUNCTION OF OVERPRESSURE

Figure 22

SUBJECTIVE REACTIONS

EQUIVALENT
FLYOVER
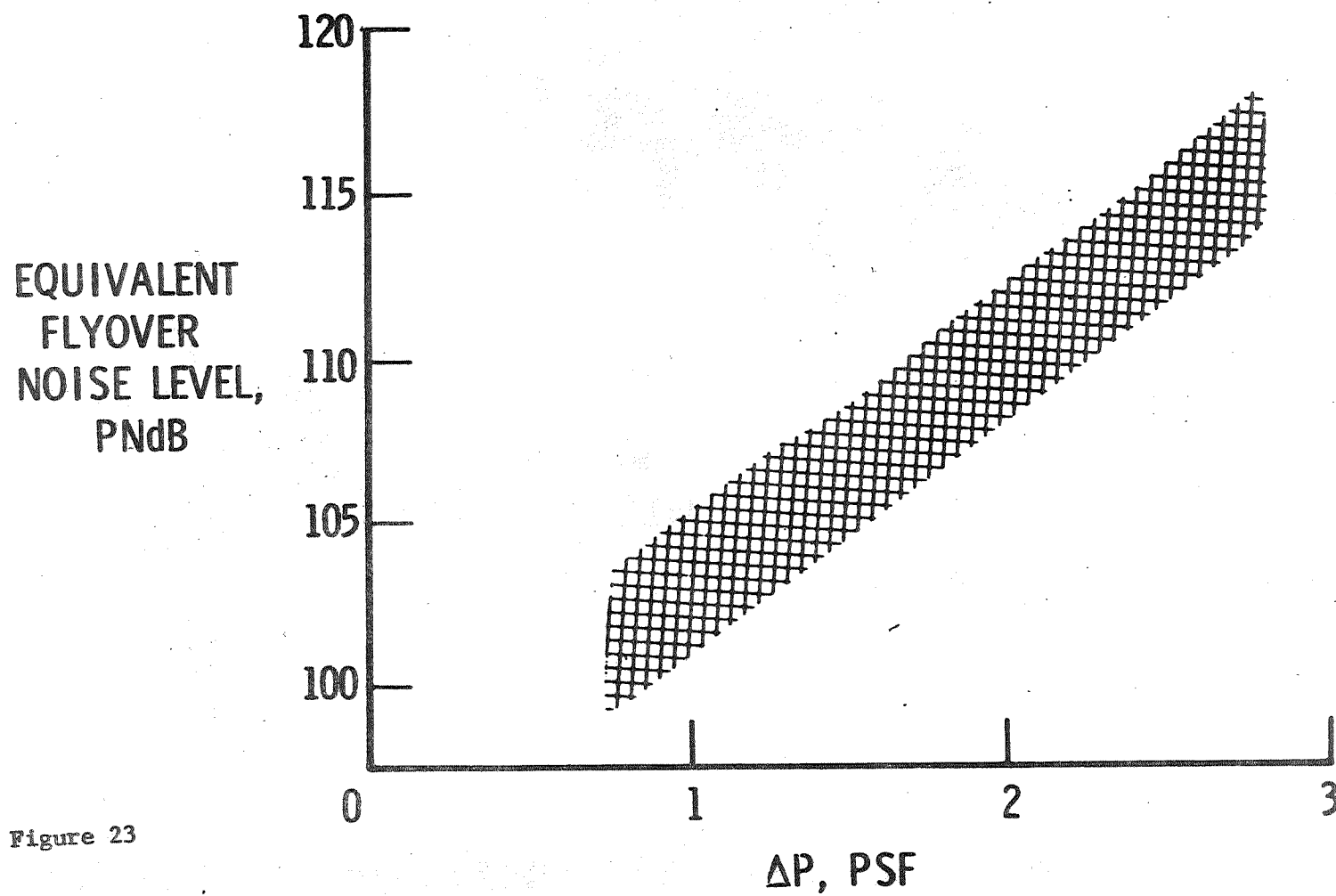NOISE LEVEL,
PNdB

ΔP, PSF

Figure 23

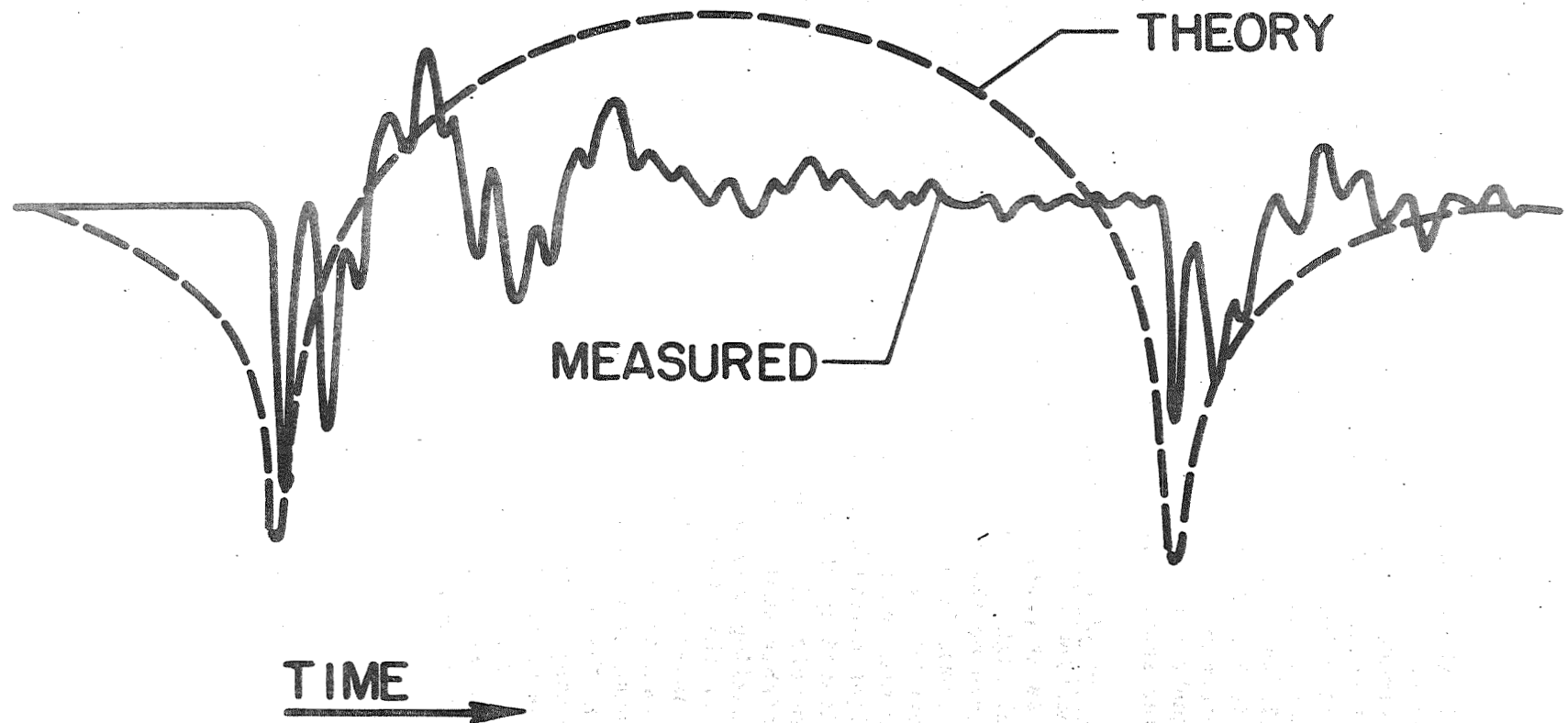# SONIC BOOM INDUCED GROUND MOTIONS
GROUND PARTICLE VELOCITY

Figure 24

and tail shockwave and are the expected motion of an elastic
surface under a transient load. The superimposed lower-amplitude
higher-frequency variations on the time history record are due
in part to the Rayleigh wave phenomena. A large number of ground
particle velocity measurements are presented in Figure 25 as a
function of sonic boom overpressure. It is noted that the maximum
particle velocity is in the order of 250 microns per second. This
value is less than one percent of the damage threshold criteria
now recommended by the U. S. Bureau of Mines. Otherwise expressed,
earthquake damage is considered to be associated with particle ve-
locities approximately 100 times the values indicated in Figure 25.

d. <u>Effects on Other Aircraft</u>. In the 1963 Edwards overflight program,
the question of possible shockwave effects from a supersonic air-
craft as it passes over a small subsonic aircraft was investigated.
Several light aircraft were instrumented for accelerations and were
overflown by the sonic boom generating aircraft which generated
sonic booms from one to 16 psf. Accelerations of the instrumented
aircraft were also measured when it was parked on the ground and
during maneuvered flights. Typical results of the sonic booms on
the light aircraft are shown in Figure 26. Normal accelerations
experienced by the aircraft on the ground are observed to be ap-
proximately 0.3 g's whereas the aircraft in cruise experienced an
appreciably smaller acceleration. By comparison, the accelerations
when taxiing over a rough runway or in air turbulence are both
shown on the figure and the latter accelerations are greater than
those experienced during the sonic boom overflights. One observer
in a Comanche aircraft noted that the 16 psf sonic boom was heard
in cruise flight as a muffled sound and that the only visible ef-
fect on the aircraft was a slight movement of the window. He was
attempting to observe the wing surface for possible oil canning
but was unable to detect any distortion due to the passage of shock-
wave. It is generally concluded as a result of these tests that
sonic booms do not constitute a hazard for other aircraft in flight
or on the ground.

SONIC BOOM INDUCED GROUND MOTIONS
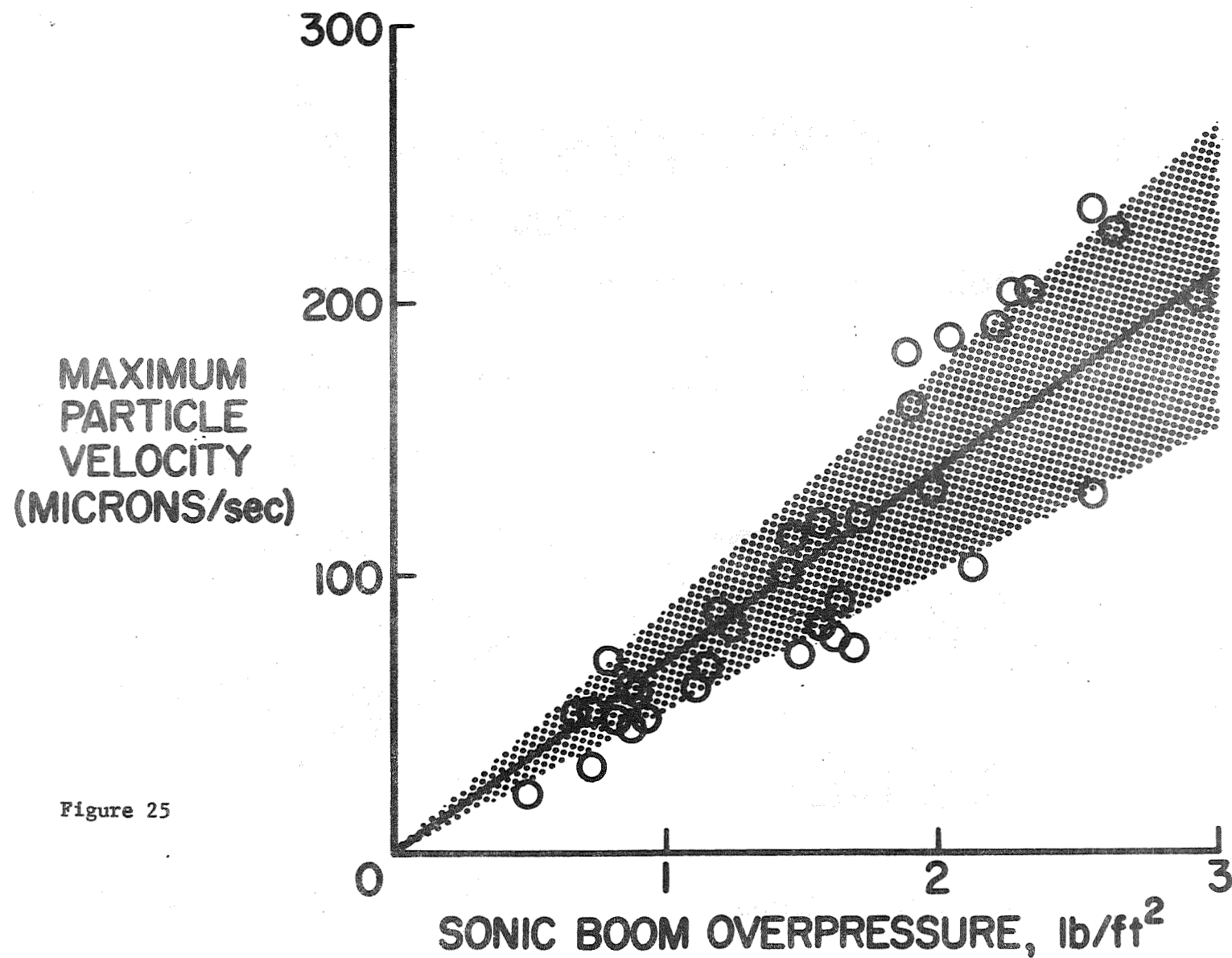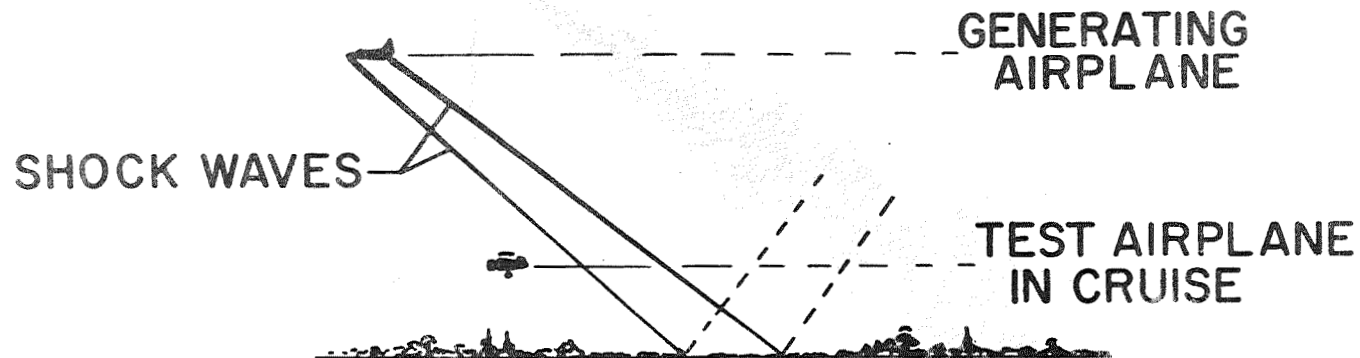

Figure 25

SONIC-BOOM EFFECTS ON LIGHT AIRPLANES

GENERATING AIRPLANE

SHOCK WAVES

TEST AIRPLANE IN CRUISE

NORMAL ACCELERATIONS

ON GROUND

CRUISE

.5g

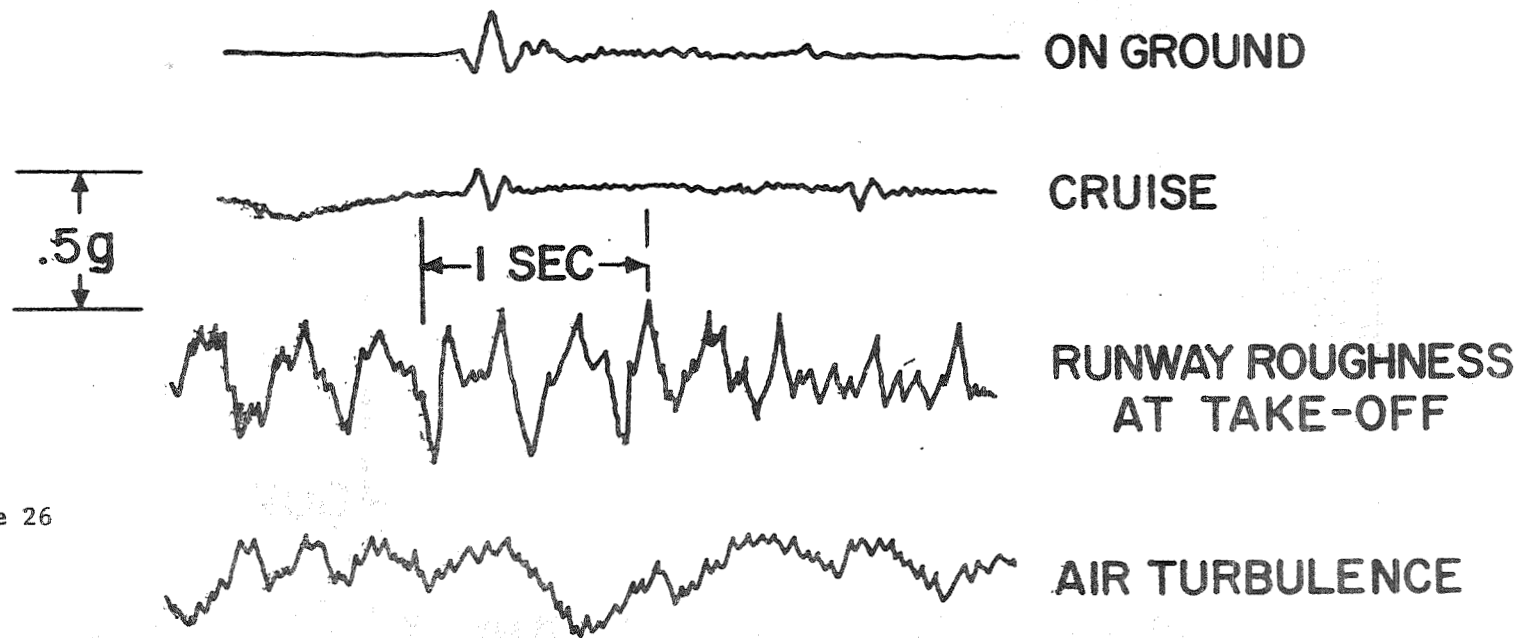|← I SEC →|

RUNWAY ROUGHNESS AT TAKE-OFF

AIR TURBULENCE

Figure 26

V. <u>COSTS OF SONIC BOOM EXPERIMENTATION</u>

The United States' active envolvement in sonic boom research has pro-
vided significant insight into the legal and social costs of this
type of experimentation. Four extensive test programs which were
conducted in a field community environment will be considered in this
section in terms of their economic aspects as measured by the asso-
ciated costs and, when appropriate, damage claims. Specifically,
these experiments are the (1) St. Louis Community Response Study,
(2) Oklahoma City, Oklahoma, Public Reaction Study, (3) Structural
Reaction Program, White Sands Missile Range, New Mexico, and (4)
Sonic Boom Experiments at Edwards Air Force Base, California.

a. <u>St. Louis Community Response Study</u>

The St. Louis program was conducted during the period July 1,
1969, through January 31, 1962, with the United States Air
Force, National Aeronautics and Space Admihistration, and the
Federal Aviation Administration participating. This program
utilized B-58 and F-106 aircraft to generate a total of seventy-
six (76) booms, over a seven-month period, with a maximum over-
pressure of 3.1 psf and an average of 2.0 psf. Since this was
basically a military training operation rather than a sonic boom
research program, overpressure and valid claims data was obtain-
able only during an 11 day period. During this period, overpres-
sures from 16 booms were recorded and 165 damage claims were in-
vestigated by professional engineers. The community response
personal interview studies consisted of a total of 1,145 initial
interviews followed by a re-interview of the respondents at a
later date. The approximate cost of obtaining the overpressure,
damage, and public reaction data was $100,000.00. The cost for
aircraft operations is not included since the training character
of the program made it difficult to delineate the purely research
costs. The final number of damage claims filed as a result of
the program was 1,624 for a value of $366,019.00, of which, 825
claims were approved by the USAF for a cost of $58,648.00.

b. <u>Oklahoma City Public Reaction Study</u>

The Oklahoma City Program was initiated on February 3, 1964, and
terminated on July 31, 1964. The program was a joint effort of
the USAF, NASA, and FAA, and was under the immediate direction
of the FAA's Supersonic Transport Development Office. FAA per-
formed the planning, direction, and management function and es-
tablished most of the operational requirements. NASA participa-
tion was primarily technical including structural instrumenta-
tion and overpressure detection. The USAF provided aircraft sup-
port and adjudication and payment of claims for all sonic boom
damage in the Oklahoma City Study area.

The public reaction was obtained through the establishment of a
telephone complaint center and periodic public opinion polls ac-
complished by the National Opinion Research Center of the Uni-
versity of Chicago. Structural reaction to the sonic boom was
evaluated by a local engineering firm, Andrews Associates, Inc.,
which investigated the response of several test houses. Addi-
tional scientific support was provided by Oklahoma State Univer-
sity. The Remmert Adjustment Company of Oklahoma City, acting
under contract to the FAA, received all alleged damage and com-
plaint telephone calls, conducted investigations of claims, and
forwarded their findings and recommendations to the Judge Advocate
General's Office, Tinker Air Force Base, Oklahoma City. This of-
fice then accomplished final adjudication and claims payment sub-
ject to normal review and appeal procedures standard with the
United States Air Force.

The overall operational aspects of the Oklahoma City program are
summarized in Table I.

TABLE I

Oklahoma City Operational Aspects

Beginning Date	February 3, 1964
Termination Date	July 30, 1964
Total Scheduled Supersonic Flights	1394
Total Flights Cancelled	141
Total Flights Completed	1253
Scheduled Flights Per Day	8
Standard Flight Schedule	7:00 a.m. 7:20 a.m.
	9:00 a.m. 9:20 a.m.
	11:00 a.m. 11:20 a.m.
	1:00 p.m. 1:20 p.m.
Scheduled Overpressures	1.3, 1.5, and 2.0 psf

In initiating the study program, there was a gradual build-up to
the sonic boom overpressure objectives. At the start of the pro-
gram, there was only one flight per day with a scheduled overpres-
sure of one psf. This was increased slowly to a schedule of eight
flights per day at one psf and then to eight flights at a scheduled
overpressure of 1.5 psf. This operational level was reached after
approximately three weeks. Then there was a similar increase from

1.5 psf to two psf which was accomplished in a manner to ensure controlled transition. The aircraft utilized in the program were the F-101, F-104, F-106, and the B-58. During the 26 weeks of the program, 15,452 telephone calls and letters were received by the complaint center; of these, 9,732 alleged damage. Four thousand nine hundred and one damage claims were filed for a value of $2,492,577; of these, 289 were approved for $19,355.00. Also as a result of this test program, seven lawsuits were filed against the United States and the Government was joined as a third party defendant by insurance companies in two other actions. Three of the cases against the United States were filed while the test program was in progress seeking injunctions to stop the program. The remaining cases sought compensation for property damage allegedly caused by the sonic booms.

The three injunction suits seeking to halt the program were dismissed and the program continued without interruption. In the remaining six cases, which seek compensation for alleged damages, the disposition is as follows: (1) The Government has successfully defended three suits totaling $101,268,984.00, (2) the plaintiffs have received compensation in two suits totaling $133,257.00, and (3) one suit for $5,439.00 is awaiting trial.

The total cost of this program including aircraft support and payment of claims was $1,039,657.00.

c. White Sands Missile Range

The Structural Reaction Program was conducted during the period November 18, 1964, through February 15, 1965. This program was designed to determine structural response characteristics for overpressures ranging from 2.0 to 28.0 psf and cumulative structural effects from repeated boom resulting from flights at a frequency of 30 per day. This study, conducted at the White Sands Missile Range, New Mexico, consisted of two phases. The first phase began on November 18 and ran through December 15, 1964, and generated a total of 615 sonic booms. The nominal overpressure ranged from 2.0 psf through 16.0 psf progressing at scheduled increments of 2.0 psf. Thirty flights were scheduled for each overpressure level. The second phase began January 15, 1965, and ended February 15, 1965. A total of 879 booms were generated during this period. The cumulative effect of sonic boom was explored by exposing structures to 680 sonic booms at a nominal overpressure of 5.0 psf. A total of 76 flights were conducted to obtain data on the effects of focusing of sonic booms due to aircraft maneuvers.

Sixteen types of structures were included in the test, seven of which were built specifically for this program. Five types of

plaster, interior finishings and a variety of commercial glass installations were studied during the two phases. Prior to program initiation, a thorough engineering inspection was conducted for each structure to establish a state of repair and overall condition. Daily inspections were conducted at 30 minute intervals on each of the structures by a 22-man engineering team.

Subsidiary test objectives included the determination of the effect of sonic booms on the hatchability of chicken eggs; human hearing impairment or adverse physiological effects caused by sonic boom at high overpressure levels; and sonic boom characteristics associated with aircraft maneuvers. The total cost of this program including construction of test structures and aircraft support was $511,100.00.

d. Edwards Air Force Base

The Sonic Boom Experiments at Edwards Air Force Base, California, were a joint effort under the management of the USAF, funded by the FAA with the NASA, ESSA, and USDA participating. The general objectives of these experiments were:

1. To measure the judgments of the relative acceptability of sonic booms and noise of various intensities from various types of aircraft.

2. To determine the response of "typical" house structures to sonic booms having different signature characteristics.

3. To obtain detailed measures of sonic boom signatures as functions of the type of aircraft, mode of operation, and the atmosphere through which the wave was propagated.

4. To observe the response of animals to the sonic booms.

The aircraft used during this program were the XB-70, SR-71, YF-12, B-58, F-104, F-111, KC-135, WC-135B, and Cessna 150. A total of 367 supersonic flights and 261 subsonic flights were accomplished. A detailed breakdown of the flights appears on the following table.

TABLE II

Edwards Experiment
Number of Overflights by Aircraft Type

SUPERSONIC		SUBSONIC	
YF-12	2	KC-135	99
SR-71	34	WC-135B	119
XB-70	20	BLIMP	6
B-58	169	C-131B	19
F-104	124	Cessna-150	18
F-106	18		
TOTAL	367	TOTAL	261

The total cost of this program, including the salaries of the observers, construction of test houses, claims, and aircraft support was $2,151.00.00.

The costs of the four research programs is summarized in Table III. The programs are listed in order of increased complexity of the test objectives. As is to be expected, the cost of sonic boom overflight experiments increased as a function of the diversity of the experiment and as a result of using advanced aircraft.

TABLE III

Sonic Boom Research Costs
($ in thousands)

St. Louis	$158.6
White Sands Project	$511.1
Oklahoma City Project	$1,039.7
Edwards AFB	$2,151.0
TOTAL	$3,860.1

VI. RECENT OVERPRESSURE INSTRUMENTATION DEVELOPMENTS

The instrumentation used to measure the sonic boom overpressures described in Sections III and IV was the culmination of many years of effort because of the special character of the sonic boom measurement problem. The spectrum of the sonic boom N wave contains appreciable energy at frequencies in the order of 0.1 Hz up to several thousands Hz and hence standard instrumentation was not adequate without extensive modifications. The development of this instrumentation is described by Hilton and Newman in Reference 13. Generally, the microphones used as the measurement systems were required to have essentially flat frequency response from nearly d.c. to the upper frequency range. In all of these recording systems, it was necessary to have experimenters in attendance to ensure continual operation and proper functioning of recording equipment.

Recently, a means of obtaining random sonic boom overflight data from unattended recording equipment has been developed. The instrument is referred to as a transient data recorder (TDR) and is currently being used in the Pendleton atmospheric program indicated on Figure 1. A picture of the transient data recorder is shown in Figure 27. The operation of the measurement equipment has been described in detail by Power in Reference 14. The recorder is self-contained and microphones are located at distances up to 500 feet from the recorder. There are three microphone pickups used with each recorder and upon arrival of a sonic boom, one of the three microphones acting on an overpressure threshold sensor activates the equipment for each of the three acoustic data channels. The recorder utilizes three equally spaced record heads on a cylindrical drum which continuously rotates inside an open loop of tape. When the signal on the threshold mike exceeds a predetermined value, a recording commences and continues for 1.6 seconds. After the recording interval the recorded tape is transferred to a storage reel while a new tape is positioned from a supply reel. By this mode of operation, the tape is advanced only during the actual recording of a signature and the expenditure of large amounts of magnetic tape while waiting for a sonic boom is avoided. As a result of this feature at least 800 independent events may be recorded on a single reel of tape. A typical TDR recording of an N wave is shown in Figure 28. It is observed that at the end of the recording period, a calibration signal is imposed giving both the amplitude of the sonic boom overpressure and the duration which is derived from a 100ms, 50Hz square wave signal. In addition to this, the date and time of day are also recorded. The transient data recorder with 99 pickup microphones is currently being used in the atmospheric effects test program at Pendleton, Ore. They have been arranged in both a checkerboard array and in a two-mile linear array. Because these recorders can operate unattended, it is possible to utilize random military overflights as the source of the sonic boom generating aircraft and the need for special overflights is avoided.

SUPPLY REEL

RECORD HEAD COVER

STORAGE REEL

TRANSPORT CONTROLS

ON/OFF TIME CONTROLS

TIME CODE GENERATOR DISPLAY AND CONTROLS

EVENT COUNTER

PEAK DETECTOR DISPLAY AND CONTROLS

THRESHOLD CONTROLS

ACCESS DOOR, RECESSED TEST PANEL
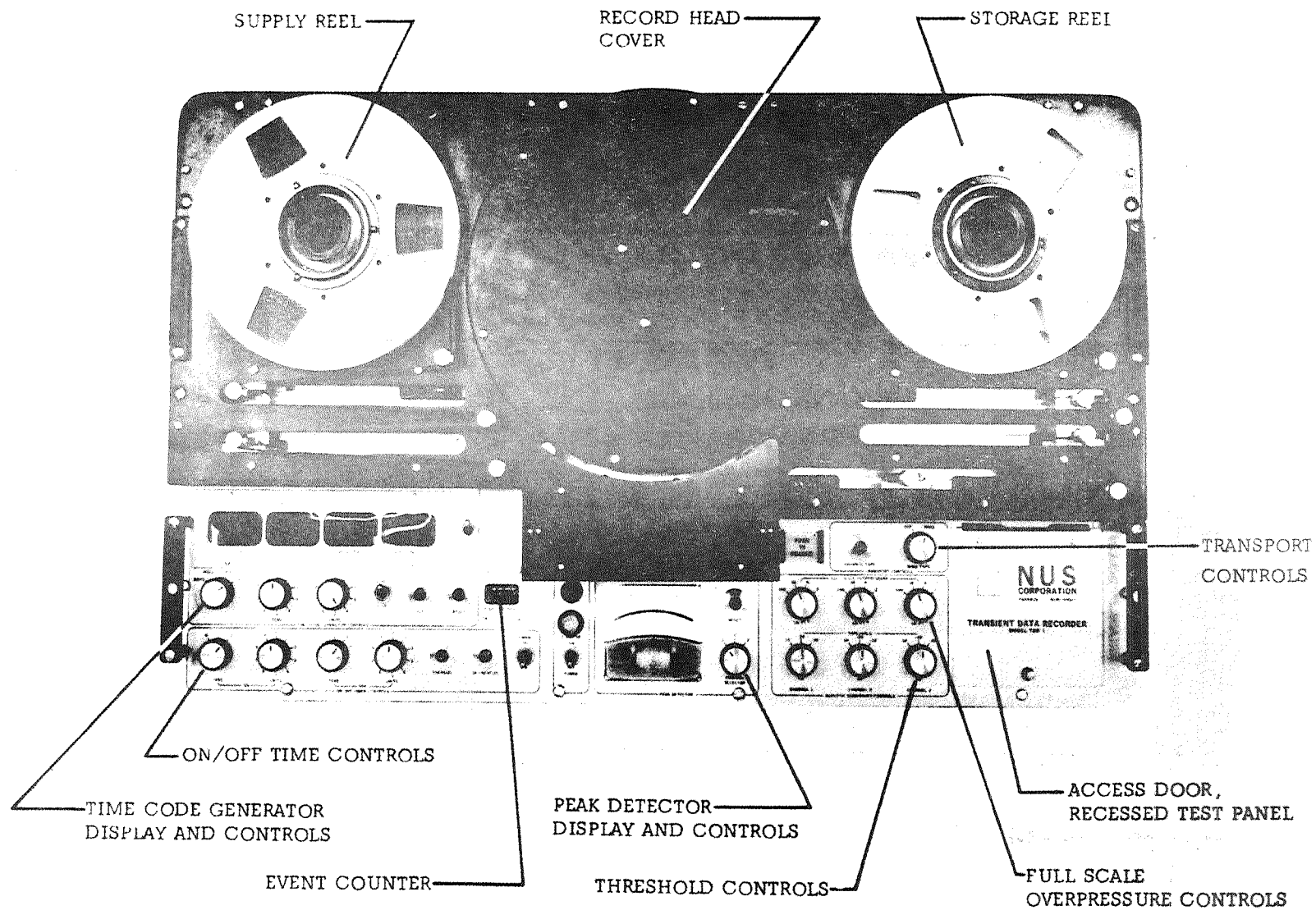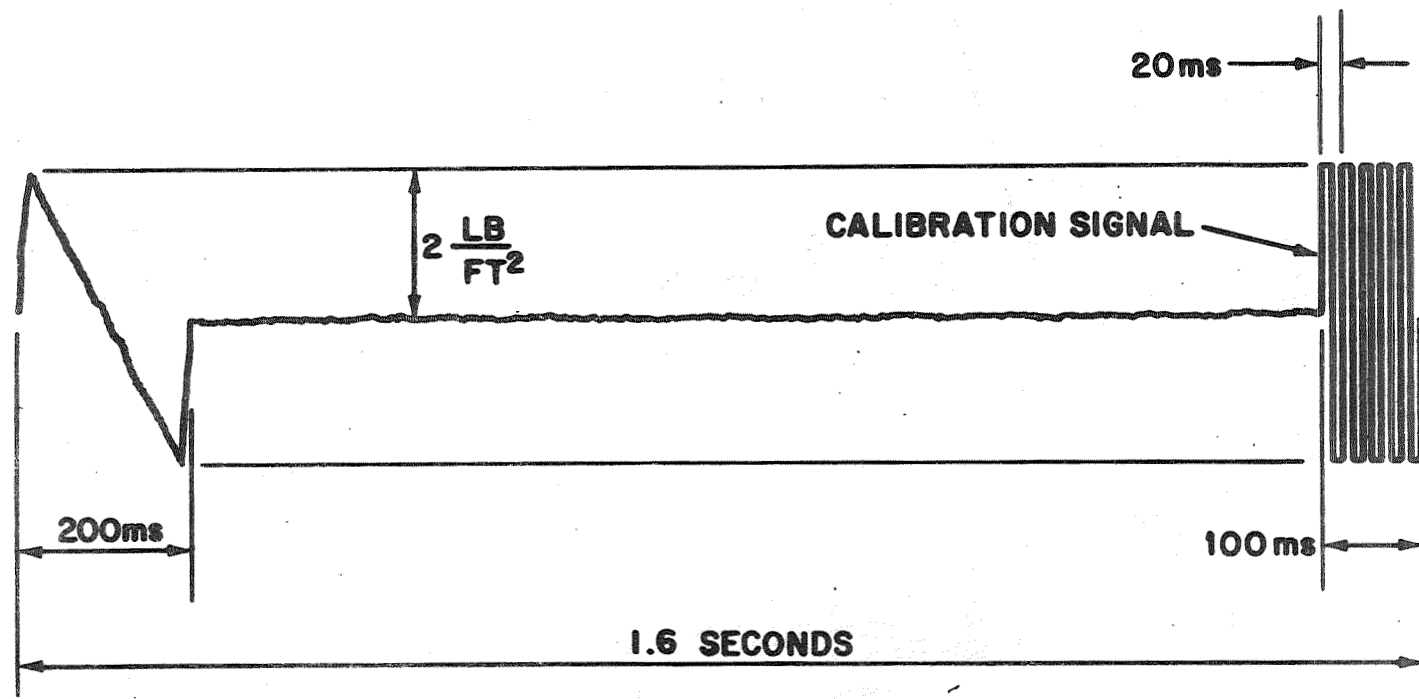
FULL SCALE OVERPRESSURE CONTROLS

Figure 27

Transient Data Recorder, Top View

TYPICAL TDR RECORDING OF N-WAVE

Figure 28

VII. RECENT DEVELOPMENTS IN SIGNATURE PREDICTION

The basis of most sonic boom signature prediction methods relies on
the developments by G. P. Whitham described in Reference 15 and sup-
plemented by the procedures of Hayes (Reference 16). These two basic
works have provided the foundation for a quasy-linear theory which
can define the sonic booms of lifting aircraft configurations in a
uniform atmosphere at some distance from the aircraft. Before these
theoretical methods could be utilized to calculate signatures for
comparison with the experimental overflight measurements described
in Section III, it was necessary to develop procedures for calculating
the propagation of the sonic boom from the aircraft to the ground
through real atmospheres. One of the early methods for computing the
propagation of sonic booms through real atmospheres was described by
Kane and Palmer in Reference 4. That method was modified by Friedman
as described in Reference 17 and also by Kane in Reference 18.

In view of the complexity of these highly numerical techniques, it
was difficult to make direct comparisons and resolve differences that
accrued from utilizing the different programs. Accordingly, a study
was undertaken by Hayes and others under contract to the NASA to
clarify the confusion existing in the area of sonic boom propagation
theories. This contract effort culminated in the development of a
sonic boom propagation technique and computer program described in
Reference 19. The procedure is based on linear geometric acoustics
and uses an age variable to define the non-linear effects on the shape
of the sonic boom pressure signatures. By so doing, the results can
be computed in the form of complete signatures, independent of far-
field assumptions necessary in other techniques. As a result, it is
possible through the use of the new program to observe the progression
of the signature shape development with distance from the aircraft in
steady flight, as a function of aircraft maneuvers and with standard
or non-standard real atmospheric effects.

a. Atmospheric Overpressure Corrections

A recent investigation (Reference 20), by Haefeli, has utilized
the new method to evaluate the effects of different atmospheric
conditions and aircraft maneuvers. One result of these calcula-
tions is shown in Figure 29. In that figure, the Mach number ef-
fects on the overpressure for an F-104 aircraft are presented in
terms of $\Delta p / \Delta p_{standard}$ where the standard value is that
for a Mach number of 1.25. On the figure, the overpressure var-
iation with Mach number in a uniform atmosphere without winds is
shown as the lower curve. The value in a standard atmosphere
without winds is also compared with the results obtained by ap-
plying the correction factor, K_A, to uniform atmosphere curve by
the method described in Reference 4. It is shown that over the
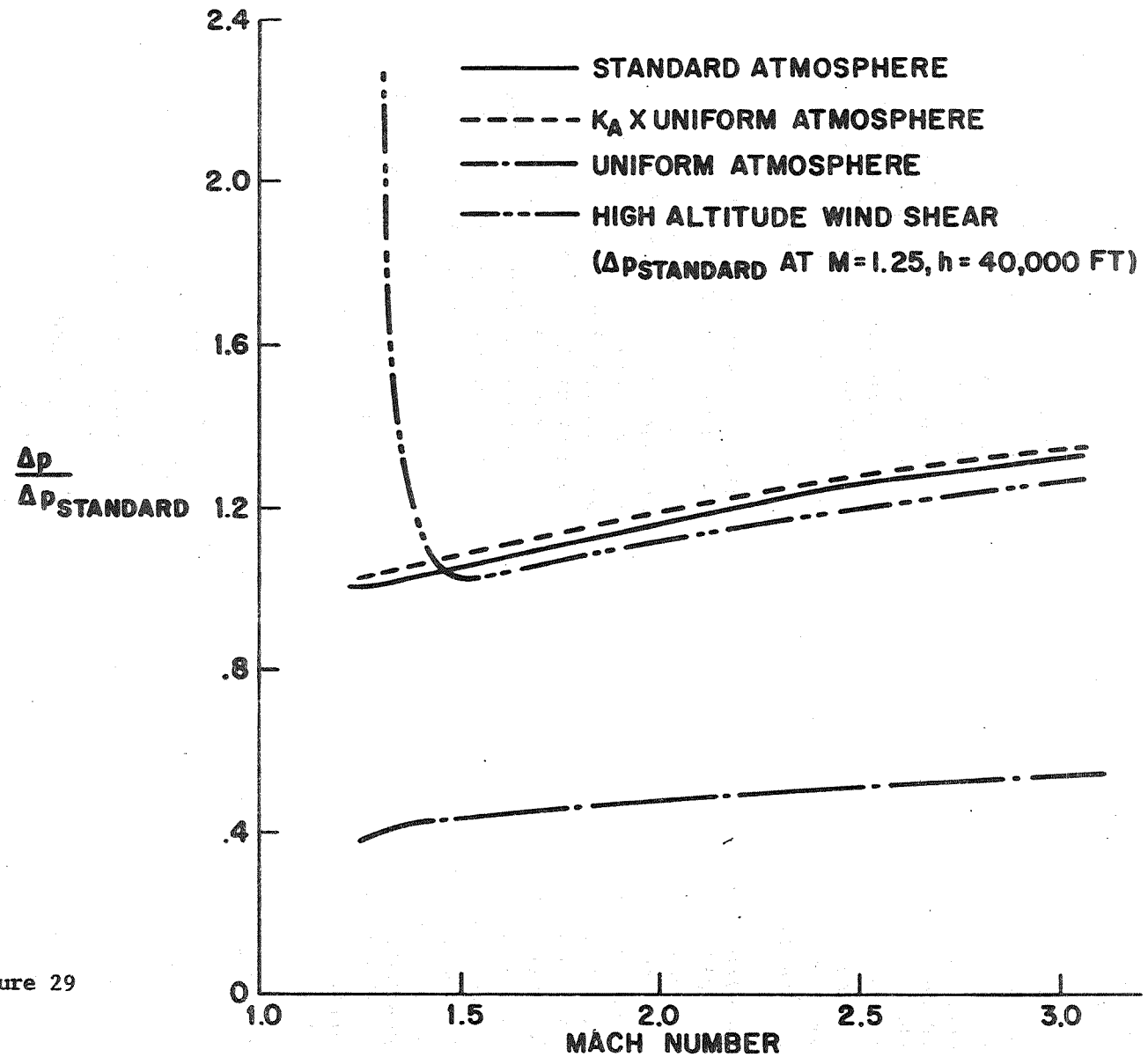Mach number range indicated and for this specific aircraft the

Figure 29

MACH NUMBER EFFECTS ON OVERPRESSURE RATIOS: F - 104

Reference 4 technique gave peak overpressure values which were essentially consistent with those of the Reference 19 method. Also presented on this figure are calculations of the sonic boom in the presence of the high altitude wind shear profile. Examination of the ray tube areas for this calculation indicated that at a Mach number of 1.3 focusing occurred just above the ground level. This is a result of the large wind decrement between aircraft altitude and the ground and yields the very large overpressure ratios.

b. While the new computational procedure compared well with the procedure of Reference 4 in the calculation of peak overpressures, the computations shown in Figure 30 demonstrate an area of potential refinement by the Reference 19 technique. In Section III.c., it was mentioned that theoretical methods previously used overestimate the signature length. In Figure 30, a comparison between the signature length computed by the two techniques is shown as a function of Mach number in terms of the signature length parameter $L_{signature}/L_{airplane}$. For the two representative aircraft chosen, namely the F-104 and the SCAT 15-F, it is seen that the computations using the uniform atmosphere, K_A, tends to give increasingly longer signature lengths as a function of Mach number than the lengths computed by the new Reference 19 method. In fact, the new procedure gives signatures which are as much as 20 percent shorter than those computed by the previous method. This result is consistent with much experimental data particularly at the higher Mach numbers.

c. Signature Aging

The most salient difference between the new method and the previous methods may be explained in terms of the amount of signature distortion which is governed by an age variable, τ. The age variable is an integral which is proportional to the distance from the aircraft and inversely proportional to the square root of the product of the atmospheric density times the ray tube area; i.e.,

$$\tau \propto \int (\rho A)^{-\frac{1}{2}} dz$$

This age variable represents the cumulation of the weak non-linear effects which result in the formation and merging of shock waves. In this Figure 31, the effects of signal aging are shown for a standard atmosphere and are compared with results obtained from a uniform atmosphere calculation. Also shown are the ray tube area variations with altitude. It is observed during the propagation from 80,000 feet to the ground, that the ray tube areas are essentially linear with altitude and tend to deviate slightly at the lower altitudes because of the increased density. A

Figure 30
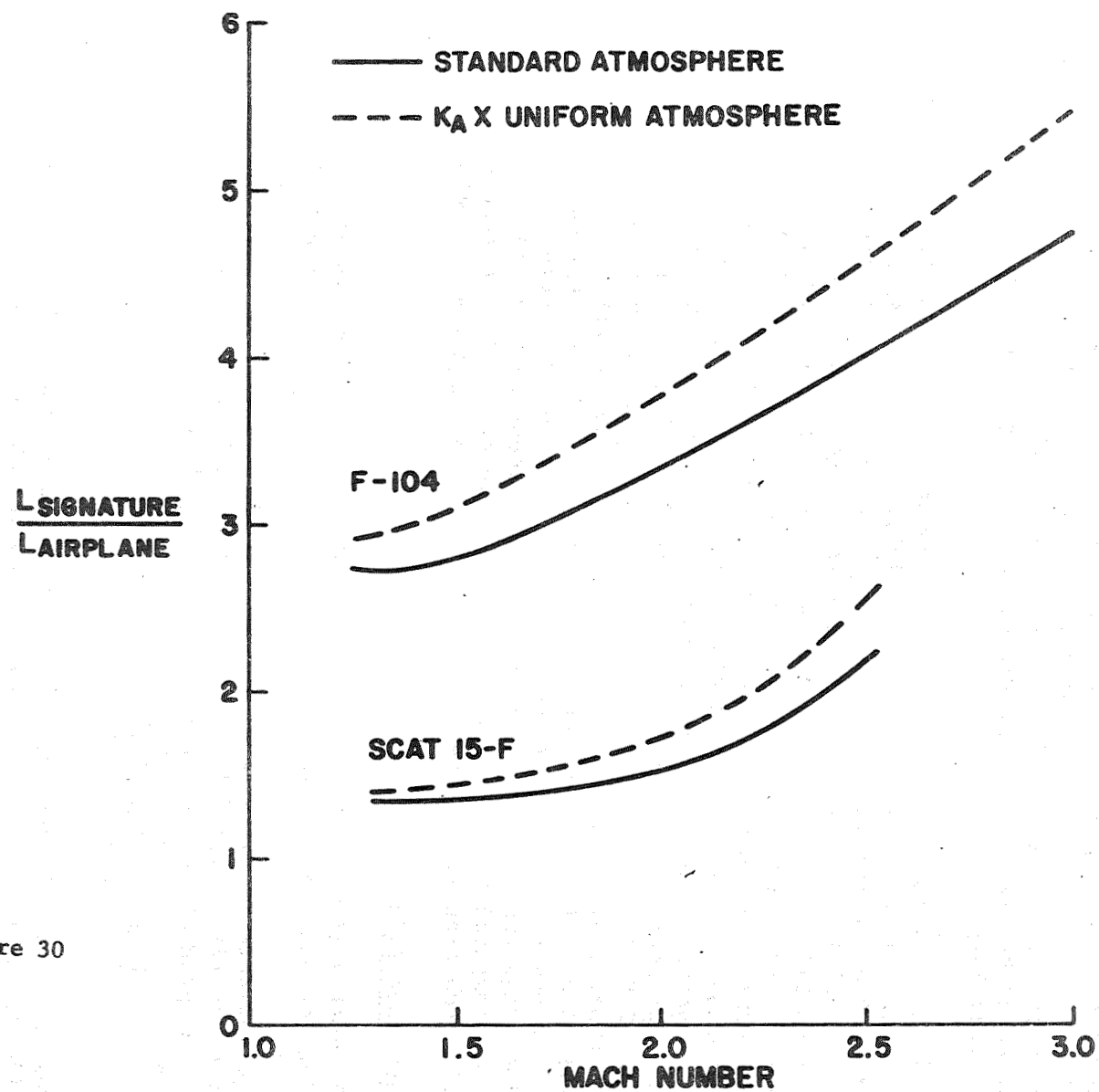
MACH NUMBER EFFECTS ON SIGNATURE LENGTH
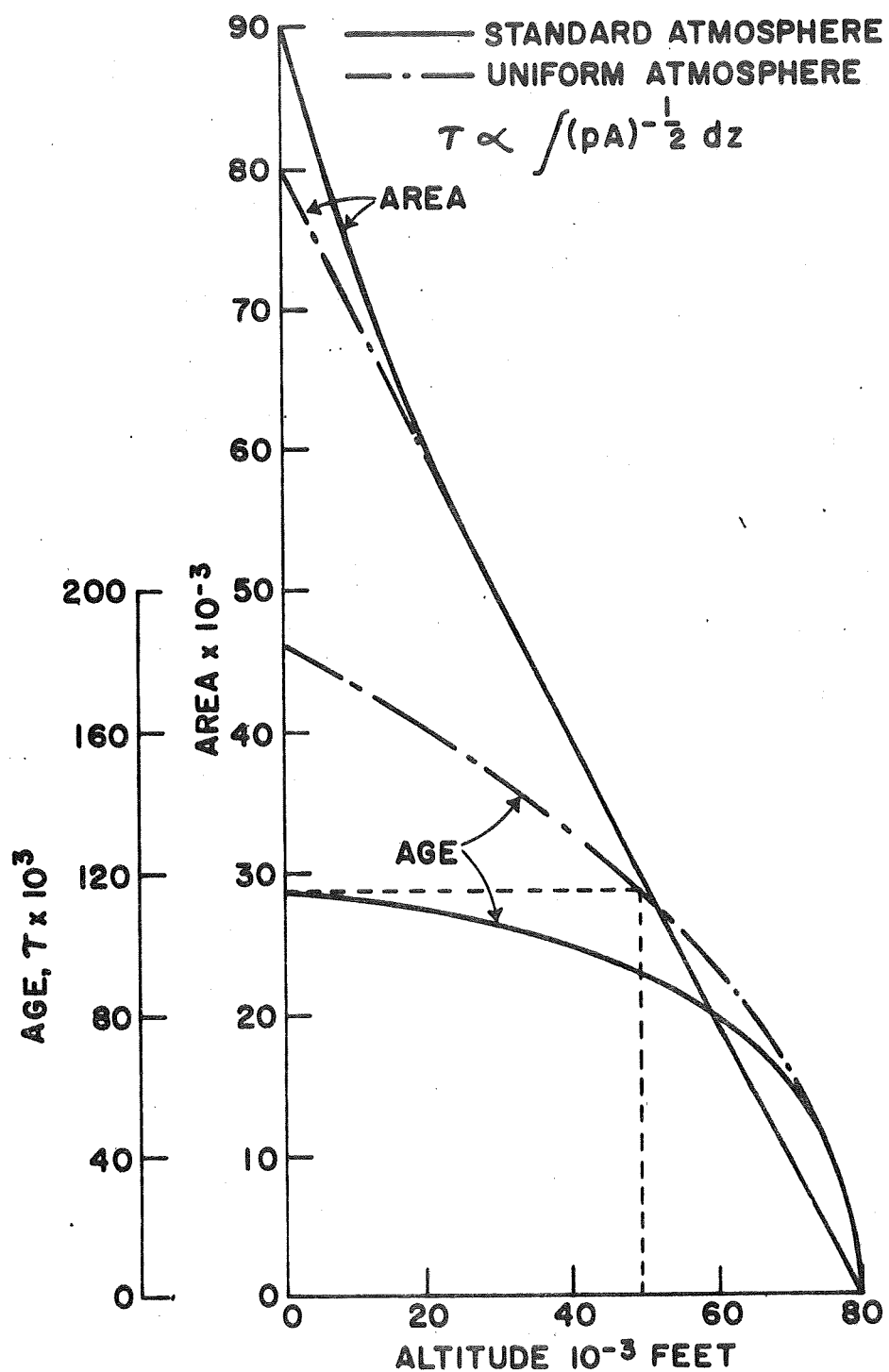
VARIATION OF RAY-TUBE AREA AND
AGE VARIABLE WITH ALTITUDE

Figure 31

significant difference, however, is noted in the age variable which for the standard atmospheric calculation tends to an asymptotic limit. In fact, the value of the age variable at approximately one atmospheric scale height (i.e., in this case, 50,000 feet), below the aircraft in a uniform atmosphere is approximately equal to the asymptotic value of the age variable in the standard atmosphere. This indicates that the asymptotic age in the real atmosphere has a finite limit and signature distortion need not continue in all cases to the classic N wave. In the uniform atmosphere, however, the age variable increases without limit and the asymptotic solution always yields an N wave. From a practical standpoint, this implies that "F" functions which are designed to produce unique signature characteristics, such as the finite rise time signatures, may in fact propagate to the asymptotic form and then proceed to the ground without further distortion.

d. Maneuver Calculations

As was mentioned previously, the ARAP Program permits the inclusion of any type of maneuvers in all planes and will yield the ground shock intersection patterns and signature shapes. Since it is based on acoustic theory, however, it will predict the location of focalization but not the magnitude of the overpressures.

An additional fact that has been developed in the Reference 20 calculations is that the changes in overpressure due to an aircraft's maneuvers may be a strong function of the aircraft's characteristics. This was observed in calculations using two different aircraft, (and hence two different "F" functions), which executed the same maneuver but experienced amplification factors differing by as much as 100%. This is illustrated by the results presented in Figure 32 which shows the change in overpressure during a pushover for the F-104 and the SCAT 15-F. For the F-104, the leading shock is much stronger in the pushover, $n_L = -0.5$, than in level flight, whereas for the SCAT 15-F, the leading shocks are nearly the same. For both aircraft the shapes of the signatures are affected greatly by the pushover which in turn is an indication of the sensitivity of the ray tube area to the rate of change of flight path angle. It must be pointed out that computation of maneuver characteristics can only be as reliable as the input data. This means that the "F" function must be continuously variable as a function of many parameters, such as: Mach number, load factor, angle of attack, etc. In the calculation to date, the "F" function variations have been accommodated by simplifying assumptions in lieu of a procedure for rapidly developing a multiplicity of "F" functions. Accordingly, this fact should be recognized as a limitation of the theoretical sonic boom prediction methods.
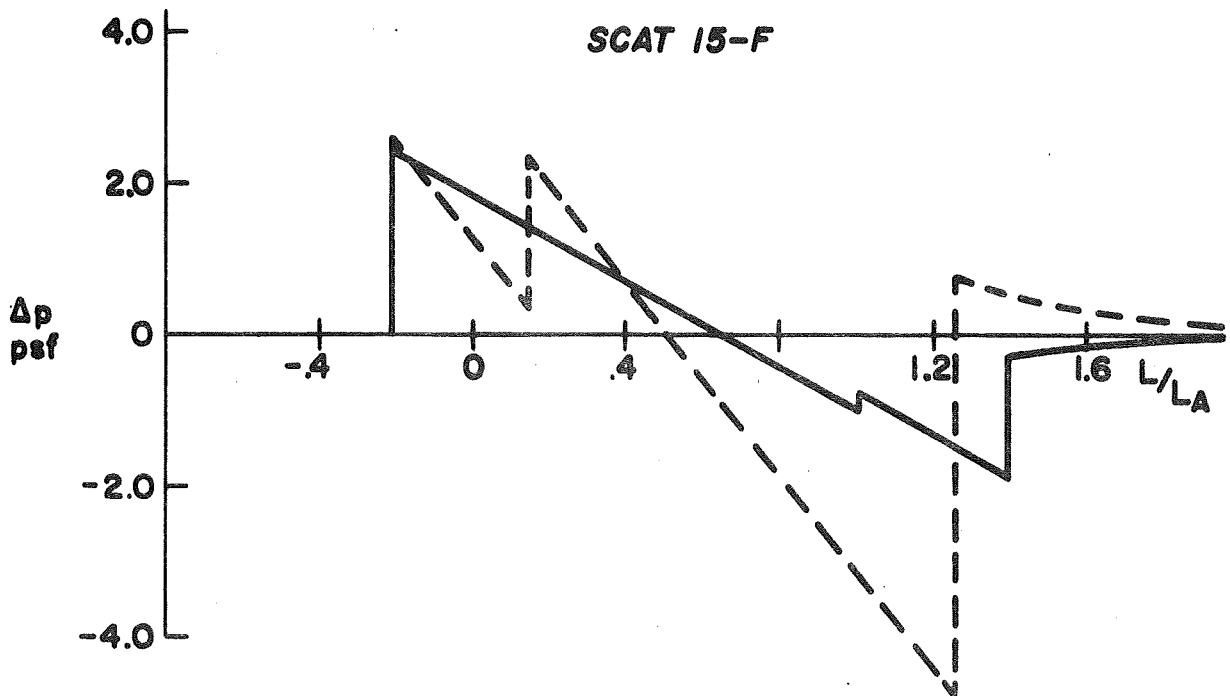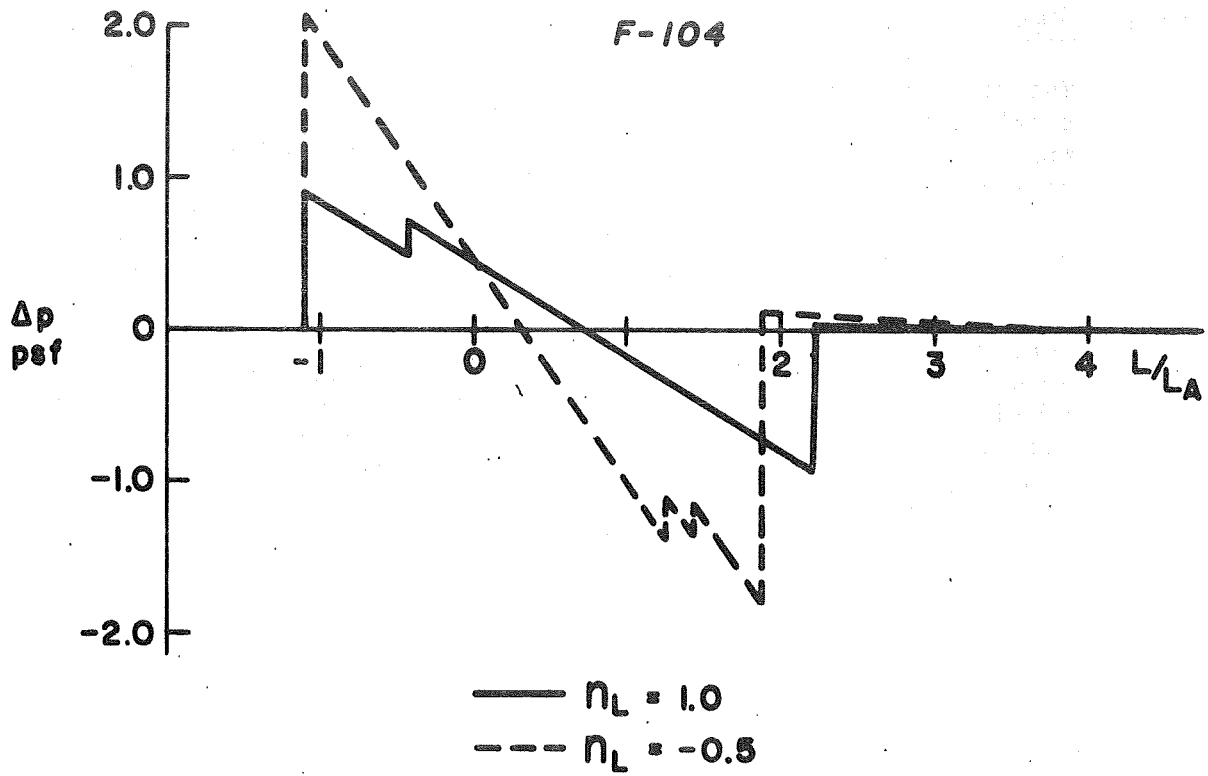
SIGNATURES FOR PUSHOVER MANEUVER
AND LEVEL FLIGHT AT M=2.0

Figure 32

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VIII. SUMMARY

The sonic boom overflight programs described in the preceding sections have generated a broad knowledge and understanding of the basic fundamentals of sonic boom generation, propagation, and physical effects on structures. The majority of the operational and maneuver related sonic boom characteristics are sufficiently well defined to preclude any unexpected results due to the overflight of supersonic aircraft. Further information is needed to identify the interactions of sonic boom with atmospheric inhomogeneities and to define psychoacoustic acceptability. One area which appears promising is the utilization of the recent knowledge of signature aging to design acceptable signatures, most probably signatures with long rise times, or what has been referred to as "bangless booms," (or "boomless bangs" for those east of the Atlantic Ocean.)

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